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HYDROGEOCHEMICAL INVESTIGATION OF REACTIVE TAILINGS AT WAITE AMULET TAILINGS SITES, NORANDA QUEBEC - PHASE 2 - 1986 PROGRAM

Final Report by

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SUMMARY

The Reactive Tailings Study (RATS) Program is jointly funded by CANMET, provinces, and the mining industry. The objective of the RATS program([1]) is to produce an inventory of practical techniques which will enable the impact of acid-generating tailings and waste rock to be sufficiently reduced so as to allow for their ultimate abandonment without the need for on-going treatment or maintenance.

In 1985, Phase 1, a hydrogeochemical investigation of the Waite Amulet tailings site was conducted by Noranda Research. In 1986, Phase 2, the subject of this report, Noranda Research completed the definition of site hydrogeology, evaluated the geochemistry of the unsaturated zone, and defined oxidation control options for 1987 field evaluation.

This report outlines the methods of investigation and discusses the results of the 1986 program with recommendations for Phase 3 work. The results of the 1986 field study indicate:

- The unsaturated zone pore water exhibited a pH generally less than 3 with elevated metals levels; pyrrhotite and pyrite was strongly oxidized in the near-surface zone and exhibited decreased to negligible alteration with depth.

- The saturated zone water had a pH generally greater than 5 with significantly lower dissolved metal levels.

- An investigation of the mineralogy in the saturated zone indicated minimal to no signs of pyrrhotite alteration.

- Monitoring the pore gas for O_2 in the unsaturated zone indicated O_2 penetration was generally less than 1 m. This is consistent with the oxidation profile, and gaseous O_2 entry may control oxidation.

The recommendations for Phase 3, the 1987 field season, are presented.

1. INTRODUCTION

The hydrogeochemical investigation of the reactive sulphide Waite Amulet tailings is part of the Reactive Tailings Study (RATS) Program which is jointly funded by Canada Centre for Mineral and Energy Technology (CANMET) and the mining industry. The objective of the RATS program is to produce an inventory of practical techniques which will enable the impact of acid generating tailings and waste rock to be sufficiently reduced so as to allow for their ultimate abandonment without the need for on-going treatment or maintenance.

In 1985, the RATS Program approved a hydrogeochemical investigation of the Waite Amulet tailings site (illustrated in Figure 1), a five-year $500,000 project funded by Noranda Inc. and CANMET. The major activities and schedule are illustrated in Table I. In 1985 a contract for Phase 1 (DSS File No. 23SQ.23440-5-9120) was issued to Noranda Research for $50,000 to conduct a preliminary site reconnaissance and drilling program. In 1986 a $225,000 contract for Phase 2 (DSS File No. 23440-6-9099/01-SQ) was issued to Noranda Research to complete the definition of the site hydogeology, evaluate the geochemistry of the unsaturated zone and define oxidation control options for 1987 field evaluation.

1.1 Study Objectives

The overall objective of the RATS Program is to eliminate the need for perpetual maintenance and water treatment for reactive tailings areas. Achievement of this objective will require the development of a better understanding of the biohydrogeochemical process and controlling mechanisms. Based on this understanding, improved long-term tailings management practises can be developed.

The second year of the five-year study is intended to:

- complete the definition of the site hydrogeology;
- evaluate the geochemistry of the unsaturated zone under clay-covered, directly-vegetated and untreated sites and along the dam face;
- define oxidation control options for 1987 evaluation.

Work Undertaken in Phase 1 indicated a uniform hydraulic gradient along the western half of the main dam. Phase 2 would finalize the site hydrogeology. It was anticipated that 20 piezometers in 6 nests would be required to finalize the tailings pore water hydrogeology and hydraulic connection between the tailings, the underlying clay layer and bedrock. Emphasis was to be placed on providing information for flownet construction for the western half of the main tailings dam.

A detailed investigation of the oxidation and migration profiles was undertaken in the unsaturated zone. The evaluation consisted of coring the unsaturated tailings, sampling the pore water, assessing the mineralogy and monitoring pore gas.

To assess any oxidation control options, a baseline determination of total metal loadings and hydraulic regime was essential. Monitoring of the precipitation and evaporation was required, as well as assessing the seepage rate and quality from the western half of the dam and the overland flow exiting the northern section of the tailings site.

1.2 Project Cost and Schedule

The 1986 project task schedule and cash flow plan is illustrated in Table II. Subcontracts were issued to Terraqua Investigations for hydrogeological work and to the University of Waterloo for unsaturated pore water geochemistry and pore gas sampling. Investigation of the mineralogy was conducted by W. Petruk and J. Jambor of CANMET, Mineral Sciences Laboratory, Ottawa. The remainder of the work was undertaken by Noranda Research.

2. METHODS OF INVESTIGATION

The following section reviews the methods of investigation for the tailings hydrogeology, pore water geochemistry, pore gas sampling, tailings and bedrock mineralogy, and the quality assurance control program.

2.1 Tailings and Bedrock Mineralogy

CANMET Mineral Sciences Laboratories (MSL), Ottawa used core samples taken during the 1985 and 1986 field season were used to evaluate the mineralogy. The methods of investigation are detailed in three reports which are included in Appendix A.

> Mineralogical and Image Analysis Study of Samples from Core WA20 of the Waite Amulet Tailings by W. Petruk and R.G. Pinard,
>
> Detailed Mineralogical Examination of Alteration Products in Core WA20 from Waite Amulet Tailings by J.L. Jambor,
>
> Mineralogical and Chemical Investigation of Cores from Piezometric Sites in Waite Amulet Tailings, Noranda, Quebec by J. L. Jambor.

Bedrock was cored by diamond drilling, and a 5 cm rock core was retrieved with a NV3 core barrel. A ten foot core sample was taken to ensure the piezometer was installed below the weathered rock surface. The core barrels were inspected on site (Appendix B) and at Noranda Research.

2.2 Tailings Hydrogeology

Piezometers were installed in the tailings, underlying clay and bedrock. Piezometers installed in the tailings were a modified Casagrande drive-point as illustrated in Figure 2. A drill rig was used to auger to approximately 1 m above the desired piezometer depth. The piezometer was advanced the remaining 1 m into undisturbed tailings with the use of the drill rig. As the augers were pulled back, a bentonite seal was placed in the borehole annulus around the piezometer to eliminate pore water or gaseous oxygen from migrating downwards to the piezometer until the tailings collapsed into the borehole.

Piezometers that were installed in the underlying clay and bedrock were conventional Schedule 40 PVC well screens. These piezometers were installed by augering in the

clay and drilling into the rock to the desired depth. The piezometer was installed inside the auger and a silica sand pack placed around and above the well screen. Bentonite was then added up to the tailings-clay interface to eliminate contamination around the borehole annulus. Details are found in the report "Hydrogeological Sampling and Instrumetation of the Waite Amulet Tailings 1986, Field Season" by R. Blackport of Terraqua Investigations found in Appendix B.

Hydraulic conductivity testing was not conducted on piezometers installed during the fall of 1986. These piezometers will be tested for hydraulic conductivity during the 1987 field season. The piezometers installed in 1986 will also be rechecked.

2.3 Saturated Zone Pore Water Sampling and Field Measurements

The water level of each piezometer was measured by using a coaxial cable water level meter. To ensure a fresh sample, all the piezometers were emptied and allowed to refill prior to sampling. Piezometers less than 8 m were emptied and sampled using a peristaltic pump. For depths greater than 8 m, a 350 mL PVC bailer (O.D. 2.6 cm) was used. During the 1985 field season, compressed nitrogen gas was used to blow out the wells. This method was not used in the 1986 field season since it coated the length of the piezometer pipe with fine tailings which were lifted from the bottom few centimetres of the piezometer tip with the pore water by the nitrogen gas. A positive displacement purge pump using nitrogen will be assessed in the 1987 field season to replace the bailer.

The wells were allowed to recover prior to pumping for samples. The samples were collected by either bailing or with the use of a peristaltic pump. When using the peristaltic pump method the pump discharge was connected to a 0.45 µm disposable filter (ACRO 50A). The bailing method disturbed the sediment at the piezometer tip resulting in too high a suspended solids which clogged the filter. The samples had to first be poured into a bottle to settle the sediments. The supernatant was then pumped through the 0.45 µm filter.

A split of the filtered sample was collected for field determinations of temperature, electrical conductance (Ec), pH, redox potential (Eh), acidity alkalinity, and ferrous iron concentrations. The remainder of the sample was fixed with HCl and

submitted to the Noranda Environmental Laboratory for analysis of Fe_T, Al, Co, Cu, Mn, Cd, Cr, Ni, Pb, Zn, Ca, K., Mg, Na and SO_4^{-2}. A separate non-acidified 275 mL bottle was used for Cl^- determination.

2.4 Unsaturated Zone Pore Water Sampling and Field Measurements

Pore water sampling from the unsaturated or vadose zone is not possible with the use of piezometers since pore water is under negative pressure. Pore water samples were collected using a immiscible fluid displacement technique. A percussion drill was used to drive a 7.62 cm diameter thin walled aluminum tubing into the tailings. The aluminum tubing was then pulled out with the aid of a block and tackle mounted on a scaffold. The tubing was then cut into 20 cm sections. Approximately 3 cm of tailings was removed from the top of each 20 cm section and filled with an epoxy plastesizer prior to mounting in the squeezing apparatus illustrated in Figure 3. Approximately 40 mL of sample was collected which was filtered with a 0.45 µm filter and a split was acidified with HCl. Field measurements were made of pH, specific conductance, Eh and Fe^{+2} on the non-acidified sample. Further details are found in a report "Hydrogeochemical Investigation of the Unsaturated Zone of the Waite Amulet Tailings Site" by D.W. Blowes and J.A. Cherry of the University of Waterloo which is found in Appendix C of this report.

In an attempt to reduce the cost and time associated with unsaturated zone sampling, suction lysimeters were installed at the Waite Amulet tailings. Figure 4 illustrates the suction lysimeter and installation method. Samples will be collected during the 1987 field season to assess their effectiveness in comparison to the fluid displacement technique.

2.5 Pore Gas Sampling

Oxidation of sulphide tailings is controlled by the availability of O_2. Transport of gaseous O_2 is orders of magnitude greater than with O_2 dissolved in the tailings pore water. To monitor the extent of entry into the tailings 0.64 cm diameter stainless steel tubes fitted with a brass tip were hammered into the tailings at different depth intervals and pulled back to allow pore gas entry between the tip and the end of the tube. In areas where tailings were cemented the stainless steel tubes buckled and could not penetrate the tailings.

A new method has been developed using 1 cm stainless steel tubing with similar brass tips. The tubes are driven into the tailings to resistance. A portable hand drill with 61 cm long 0.64 cm diameter bit was used to drill through the cemented tailings. The tubing and brass tip was then installed and hammered to the desired depth. The inner annulus of the stainless steel tubing is filled with a polyethylene tube to reduce the required pore gas volume for sampling. This method has been tested in May of 1987 and will be used during the 1987 field season.

2.6 Surface Runoff, Seepage, Precipitation and Evaporation Monitoring Equipment

Monitoring equipment was required to evaluate the water budget and metal movement into, through, and out of the tailings. First, precipitation and evaporation were to be monitored to assess water available for infiltration and runoff. Runoff from the surface of the 40 hectare site can only exit at the ditch at the northern edge of the tailings. This site therefore required a monitoring station to assess the runoff flowrate and its water quality. The 1985 examination of the geochemistry and hydrogeology of the infiltrated pore water indicated that the majority of porwater reports to the perimeter of the tailings dam proper. Therefore a station is also required to assess seepage rates and water quality of the western half of the dam seepage discharge. (It is assumed that this would be representative of the seepage for the whole dam).

The two station locations are: one on on top of the tailings at the northern section to monitor precipitation, evaporation and surface runoff and water quality; the other along the western seepage face to monitor seepage quantity and quality. The flow is monitored with a Hinde Engineering Accura-flow H flume equipped with a float pot water level. The water samples are collected with a 24 bottle American Sigma Model 6201 automatic sampler, triggered by a preset total flow. Signet pH probes are installed downstream of the flumes. Precipitation is monitored with an OTA 34-T tipping bucket rain gauge. Evaporation is monitored with a Qualimetrics Model 6844-A gauge and evaporation pan. A Lakewood LE8305C data logger will be used to store the data until retrieval with a Toshiba T1100 lab top micro-computer with 640K memory. This equipment is powered by lithium and marine batteries.

2.7 Quality Assurance and Control Program

Several measures were taken to minimize saturated zone piezometer sample contamination:

- Sample bottles were acid washed using a HCl/HNO_3 mixture and rinsed with distilled water.
- Sampling equipment which included the sample tubes and hand-operated bailer were carefully rinsed with distilled water prior to sampling each piezometer.
- Each filter was disposed of after one use.
- All sample tubes were not allowed to touch the tailings and were hung up when not in use.

Quality control of analytical results was assessed with the use of three different concentrations of spiked samples (containing Co, Cu, Fe, Ni, Mg, Mn, Pb, Zn, and Ca), two series of five field replicates, two field blank samples and four blank samples. The spiked samples were required to assess reproducibility, accuracy and bias in the analysis. The field replicates were made up from the same piezometer sample to assess reproducibility. The field blanks were distilled water which was passed through the sampling equipment to assess contamination in the sampling method.

The results of the quality control program are detailed in Table III. Reproducibility for the high metal level standard was in general good since the coefficient of variation was less than 17%. The accuracy was also good based on a relative error less than 15%. Laboratory analysis of the medium metal level standards showed good reproducticibility except for Cu, Pb and Zn at 0.1, 0.5, and 0.1 mg/L respectively, where the coefficient of variation was greater than 30%. The accuracy was good except for Cu, Ni and Zn where the relative error was greater than 40%. The low metal level standard was below most the metals detection limits.

Reproducibility was also checked at two piezometer locations using five replicates from each piezometer. Reproducibility on the first set was good on Fe, Mg, Mn and Ca with a coefficient of variation less than 10%. However, with Co, Ni, Pb, and Zn, the coefficient of variation was greater than 20%. The second set of the replicates was near the detection limit therefore the assessment of reproducibility was not possible.

Analysis on the blanks and field blanks were almost all below the detection limit. This suggests that no significant contamination occurred during sampling and analysis.

At all times, reproducibility and accuracy for Fe, Ca, Mg, and Mn (and Zn at high levels) was excellent. Considering the low levels (except Fe, Ca, Mg and Mn) obtained during the pore water sampling survey and their negligible significance on water quality (i.e. no impairment), the poorer reproducibility noted above for some elements at low levels does not have a significant impact of the overall quality of the results.

The method of sample collection in the unsaturated zone only produced approximately 40 mL of sample which was insufficient to assess reproducibility by replicates. A good degree of quality assurance was obtained by:

- acid washing all equipment prior to use for sample collection;
- attempting pore water squeezing in an anaerobic state to reduce further oxidation or alteration of sulphides;
- conducting immediate determinations of pH, specific conductance, Eh and temperature.

Quality control of analytical results was assessed with the use of spiked samples and blanks as stated above. Due to the limited sample size (40 mL), acidity and alkalinity were not performed. Replicates for field determination of Fe^{+2} are detailed in Appendix B, Table XI. Blanks, spikes and duplicates, and the pore water samples were submitted to the Noranda Environmental Laboratory. Detailed analysis of the quality control data are being conducted by D. Blowes, University of Waterloo.

The preliminary indication is that the coefficients of variability are relatively high due to small sample volume.

3. RESULTS AND DISCUSSION OF THE 1986 FIELD PROGRAM

3.1 Tailings and Bedrock Mineralogy

An initial examination of the mineralogy by Petruk and Pinard found in Appendix A on piezometer site 20 indicated that: in the unsaturated zone the sulphides were nearly depleted with 5% pyrite and pyrrhotite; in an intermediate level above and at the water table there was 25% pyrite and 6% pyrrhotite; and below the water table where there was minimum alteration with 60% pyrite and 14% pyrrhotite. This work was confirmed with subsequent work by Jambor (Appendix A). The principal alteration products were goethite, sulphur and ferrous sulphate. Piezometer site 20 is on the bench and the pore water is from infiltration as well as pore water movement from the main dam. The water table will fluctuate along the bench more readily than on top of the tailings. Therefore, this site is not representative of the alteration profile which might exist for the main tailings dam. Consequently, it was decided to first assess the mineralogy and alteration products below the water table in the main dam prior to evaluating the unsaturated zone. Core samples which were collected during the 1985 field program and retained frozen were utilized. Figure 5 illustrates the piezometer sites from which cores were collected. To relate the mineralogy to tailings pore water only cores which were adjacent to the piezometer well screen were submitted to CANMET for evaluation.

The mineralogical investigation of 31 core samples from the saturated zone was conducted by J. Jambor (Appendix A). Table IV summarizes the microscopic investigation of the tailings. The results indicate only local grain alteration of pyrrhotite grains which would have taken place during the operating life of the tailings dam. As these tailings had been spigotted out, they would have been exposed for months prior to being covered by the next lift of tailings.

Investigation of the unsaturated zone mineralogy is currently under way by J. Jambor and will be reported separately.

Investigation of bedrock integrity and hydraulic conductivity was conducted at piezometer locations 2 and 9. The bedrock cores were inspected in the field (Appendix A) and subsequently inspected by D. Milne at Noranda Research. A 2.46 m rock core was collected at station 9. The rock is a medium to fine-grained granodiorite. 2.29 m of core was recovered from this hole for a 93% recovery. The rock quality designation (RQD) from this hole was about 80%. Some core grinding is apparent at the top of the hole which would account for the lost core. Minor surface staining is present on some joint surfaces, probably due to the shallow nature of the holes. Some steep ($60\text{-}90^{o}$) joints are healed with calcite and show a minor amount of solution prior to mining. In general, the core quality is good, showing only minor surface weathering effects.

A 3.06 m of core was retrieved from a drill hole at piezometer location 2. The rock is a medium to very fine-grained diorite. Core recovery was 100% from this hole with an RQD of about 85%. A minor amount of surface staining is present on the joint surfaces. A steep set of joints dipping $\sim 80^{o}\text{-}90^{o}$ is present and is sometimes healed with calcite. Other joints appear to dip between $30^{o}\text{-}60^{o}$. The core quality is good (slightly better than at 9) and shows only minor surface weathering effects.

3.2 Tailings Hydrogeology

A total of 74 piezometers has been installed at the Waite Amulet tailings of which 21 were installed in the 1986 program. There are 66 piezometers in the tailings, 6 in the underlying clay and 2 in the underlying bedrock. The water table obtained from measurements in the shallowest piezometer at each nest is illustrated in Figure 6. The contours were constructed using a computer program (Surfer from Golden Software Inc.). The water table configuration is similar to that reported in the 1985 field program([2]). Figures 7 to 13 illustrate the water table profile in Sections A-A to G-G.

3.3 Tailings Pore Water Chemistry

3.3.1 Saturated Zone Porewater Chemistry

The 74 piezometers were sampled in October-November of 1986. The piezometer nest locations are illustrated in Figure 5. There are 66 piezometers installed in the tailings, 6 in the underlying clay and 2 in bedrock. The field determined analytical results and elevations are illustrated in Table V which includes the sample date, ground elevation, elevation of the piezometer well screen, elevation of water in piezometer, pH, Eh, Ec, acidity and alkalinity. Table VI details the pore water ion concentrations for Fe^{+2}, Fe_T, Al, Co, Cu, Mn, Cd, Cr, Ni, Pb, Zn, Ca, K, Mg, Na, SO_4^{-2} and Cl^-. The analysis of Fe^{+2} was field determined.

The pH in the saturated zone is greater than 5. There is little evidence of vertical profile trends in pH in the saturated zone. The pH of the unsaturated zone pore water detailed in Appendix C, Table 1-9 was generally less than 3 near surface and increased with depth. The redox potential was similar in the saturated zone to that of the unsaturated zone (see Appendix C). The uncorrected Eh values reported in Table IV for the saturated zone are the same order of magnitude as the unsaturated zone specific conductanc reported in Appendix C. The saturated zone pore water exhibits acidity less than 100 mg/L as $CaCO_3$ with the exception of high levels from piezometers 1,2 4-2, 11-3, 12-1, 13-1, 14-1, 18-5, 20-2, 21-2, 22-3, 22-4,25-1, 26-4, and 27-1. These high levels are probably due to one of the following:

- The piezometer well screen is close to the interface of the saturated and unsaturated zone where the migration of acid water in the unsaturated zone has reduced the buffer capacity of the tailings surrounding the well screen.

- Piezometers positioned on the side slope of the dam are influenced by a variable water table at the seepage face as well as a coarser tailings fraction which increases air entry providing an accelerated oxidative environment.

- Shallow piezometers may have only a few centimetres of water cover over the sediments at the bottom of the well screen and may periodically dry out resulting in the oxidation of the tailings.

The Waite Amulet saturated zone pore water ion concentrations are detailed in Table VI. The analysis indicates that for Cu, Co, Mn, Cd, Cr, Ni, Pb, Zn and the majority of Al levels are at or below the detection limit. Therefore these elements will not be monitored for in future sampling programs in the saturated zone. The predominant anion is SO_4^{-2}. The Fe^{+2} and Fe_T results indicate that the majority of the iron is as Fe^{+2}. The determination of the Fe^{+2} was determined in the field by a titration method whereas the Fe_T was by atomic absorption.

Figures 7 to 13 illustrate the piezometer well screen location in Sections A-A to G-G. The acidity as $CaCO_3$, SO_4-2, Fe_T and pore gas O_2 are plotted with depth at each piezometer nest. The results are found in detail in Tables IV-VI and in Appendix C. The unsaturated zone results are approximately 20 cm intervals with depth. In the saturated zone the results are from the piezometers and the results inferred between piezometers.

Piezometers installed in bedrock were at stations 9 and 2 in Figures 11 and 13. These piezometers had not been pumped sufficiently to remove any contamination during drilling and recovery was slow. Therefore it was planned to pump them out a number of times during the 1987 field season to ensure a representative sample.

The underlying clay pore water was sampled at piezometer locations 18-1 , 17-6, 10-2, 27-1, 9-7, and 15-3 illustrated in Figures 7, 8, 10, 11, and 12. The southern section of the tailings area where piezometers 18 and 17 are situated experiences little migration of pore water downwards. The clay in this area may be in excess of 20 m and not weathered providing a good barrier. Piezometers in the central and northern portion indicate moderate to high levels of Fe and SO_4^{-2}. Piezometers installed in clay and the underlying bedrock may not be flushed sufficiently to obtain a representative sample.

Analysis of the saturated pore water chemistry indicates a decrease in concentration of Fe_{-2} and SO_4^{-2} with depth below the water table. This is a result of the neutralization of acidic pore water from the unsaturated zone by the tailings buffering capacity. However, the elevated acidity levels in the shallow piezometers suggest that pH will decrease with time with resultant elevated metal levels.

The anomoly of high SO_4^{-2} for piezometer 24-4 may be due to sample or analytical error.

3.3.2 Unsaturated Zone Pore Water Chemistry

The pore water in the unsaturated zone was assessed at eight sites which included piezometer nest location 22, 20, 11, 24, 17, 21, 8 and 2. The results for Fe_T and SO_4^{-2} are plotted with depth in Figures 7, 8, 12, and 13. Detailed results are found in Appendix C. The oxidation of sulphides, mainly pyrite and pyrrhotite, produced low pH conditions and high concentrations of Fe^{+2} and SO_4^{-2} and high concentrations of Cu, Pb and Zn. The Eh in the 400-700 mV range (Appendix C, Tables 1-8) indicating an abundance of oxidized species in the pore water. Analysis for acidity and alkalinity were not performed on the unsaturated zone samples due to the small sample volume.

The water table in the northern section of the tailings dam is near surface, as illustrated in Figures 11-13. The unsaturated pore water at piezometer sites 8 and 2 illustrated in Figures 12 and 13 respectively indicated a shallow water table. The Fe_T level was approximately or less than 1000 mg/L with a corresponding SO_4^{-2} less than 5000 mg/L. In this area the tailings are assumed to be fine grained.

In the coarser tailings (such as along the tailings bench at stations 20 in Figure 8 and station 21 in Figure 12, and areas with a deep water table and coarser tailings fraction as with stations 22, 11, 24 and 17 in Figures 7 and 8), the extent of oxidation is more pronounced with Fe_T generally in excess of 2000 mg/L and SO_4^{-2} in excess of 5000 mg/L. The first few centimetres are generally lower in metals due to neutralization with limestone during reclamation of the site in 1979-1980. This upper zone is being depleted of sulphides (see Section 3.1) and sulphides are being consumed at depth in the unsaturated zone. The oxidation products are progressing downwards and being neutralized by the buffering capacity of the tailings. This trend can be seen in Figure 8 at piezometer locations 20, 11, 24 and 17. The neutralization capacity by carbonate minerals in the tailings neutralizes the acid pore water to raise the pH and retard the movement of low pH and high metal concentrations in the pore water as it reports to the water table.

3.4 Gaseous O_2 Profiles

The oxidation of sulphides will progress more rapidly due to oxygen diffusion rather than dissolved oxygen transported with pore water since the diffusion of oxygen through air is orders of magnitude greater than diffusion of oxygen through water. Oxygen diffusion may be the rate limiting step([3]) in oxidation of sulphides. Oxygen penetration into the tailings is governed mainly by, moisture content, the location of the water table, the tailings particle size, the presence of hardpan or cemented tailings and the amount of sulphides available. If the tailings have a high sulphide content, oxygen will be consumed at a shallow depth.

The entry of gaseous O_2 is limited by the high water table at piezometer site 2 illustrated in Figure 13. Figure 8 illustrates the O_2 profiles for piezometer sites 20, 11, 24 and 17. Oxygen penetration was limited to less than 1 m. This may be the result of sufficient sulphides which deplete O_2 and/or a cemented layer of tailings restricting O_2 entry.

The sampling of O_2 below the clay cover (piezometer site 24) was insufficient to assess the effectiveness of the clay cover in limiting the entry of oxygen. A more detailed study has been recommended for the 1987 field season.

3.5 Technology Transfer

Five presentations regarding the Waite Amulet hydrogeochemical investigation were made:

- 1986 National Symposium of Mining, Hydrology, Sedimentology and Reclamation, Lexington, Kentucky, December 1986
- Canadian Mineral Processors Operators Conference, Ottawa, Ontario, January 1987
- Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia, March 1987
- Quebec Metal Mining Association Workshop, Val d'Or, Quebec, May 1987

. Air Pollution Control Association, Montreal, Quebec, May 1987

Copies of the Kentucky, Halifax and Montreal papers are found in Appendix D.

4. RECOMMENDATIONS

The proposed third-year field program of the five-year study will([4]):

- Evaluate the hydrogeochemistry of the tailings site including a water and metal balance.
- Evaluate gaseous O_2 profiles under clay-covered, directly-vegetated and untreated sites.
- Relate the mineralogy to the unsaturated pore water geochemistry.
- Assess oxidation control options for field trials.

4.1 Evaluate Hydrogeochemistry

The 1987 field program will provide a baseline monitoring of metal loadings and flow for the Waite Amulet tailings site. The precipitation and evaporation will be monitored and the data logged by equipment installed in July 1987 as part of the Phase 2 project.

Pore water movement and geochemistry will be evaluated using the 73 installed piezometers. The piezometers will be sampled twice during the 1987 field season. Field analysis will consist of pH, Eh, Ec, temperature and acidity. The samples will be preserved for subsequent analysis of Fe^{2+}, Fe_T, SO_4^{2-}, and possibly Mg, Ca and Na at the Horne Division Environmental Laboratory. Shallow wells may be monitored for other metals with increased acidity levels. The 73 piezometers will be measured weekly or bi-weekly to monitor the water table fluctuation with rainfall events.

The western seepage face will be monitored for flow and quality using a flume and automatic sampler with data logger. Overland flow at the northern section of tailings will be monitored for flow and quality using a flume and automatic sampler with a data logger. The automatic samplers will be calibrated to flow and checked routinely. The samples which are field preserved will be submitted to the Horne Division Environmental Laboratory for analysis of Fe^{2+}, Fe_T and SO_4^{-2}.

The four suction lysimeters installed during the 1986 field season will be sampled to assess their effectiveness in sampling the unsaturated zone. It will then be decided whether and where the remaining eight lysimeters should be installed.

This data acquisition program will continue for a three-year period (1987-1989). Factors affecting the water quality and flow through a tailings dam will then be more clearly understood.

4.2 Evaluate Gaseous O_2 Profiles

A more complete survey of gaseous O_2 profiles will be conducted on the Waite Amulet site to assess diffusion into the tailings. A grid pattern will be established over the forty hectare tailings site and O_2 will be monitored with depth. A core sample will also be taken to measure the visual depth of oxidation, moisture content and grain size distribution. This is an extensive survey and is expected to be completed during a four month period with the aid of a summer student.

4.3 Relate Mineralogy to Pore Water Chemistry

Dr. J. Jambor, MSL, CANMET, is currently investigating the mineralogy of the unsaturated zone at eight sites which were squeezed for pore water by D. Blowes, University of Waterloo. The unsaturated pore water geochemistry, O_2 profiles and mineralogy will be then correlated.

4.4 Assess Oxidation Control Options

Via a separate project, laboratory methods([5]) for evaluating dry barriers for oxidation control are being developed. Field trials of the options under consideration will be scoped. (Note that funds for conducting such field tests have not been allowed for in this project).

4.5 Use of RATAP Model

A computer model has been developed as part of the National Uranium Tailings Program for use on reactive tailings. It is recommended that this model be evaluated at Waite Amulet in conjunction with and compared to modelling conducted by D. Blowes, University of Waterloo. This work is outside the scope of this project.

REFERENCES

1. Monenco Ltd., Cominco Ltd., Inco Ltd., and Noranda Inc., Sulphide tailings management study, Report to CANMET, DSS 8032-8, 29 June 1984.

2. Siwik, R.S., Noranda Research Centre, Hydrogeochemical investigation of reactive tailings at the Waite Amulet tailings site, Noranda, Quebec, 1985 Program. DSS Contract OSQ85-00101, July 1986.

3. Nicholson, R.V., Pyrite oxidation in carbonate-buffered systems. Experimental Kinetics and Control by Oxygen Diffusion in a Porous Medium. Ph.D. Thesis, University of Waterloo, 1984.

4. Wheeland K., Noranda Research Centre, letter to Dr. N. Dave CANMET, Elliot Lake Laboratories, April 27, 1987.

5. Noranda Research Centre, Beak Consultants, and University of Waterloo, Development of laboratory methodology for evaluating effectiveness of engineered cones for reactive tailings, DSS Contract 23317-6-1737.

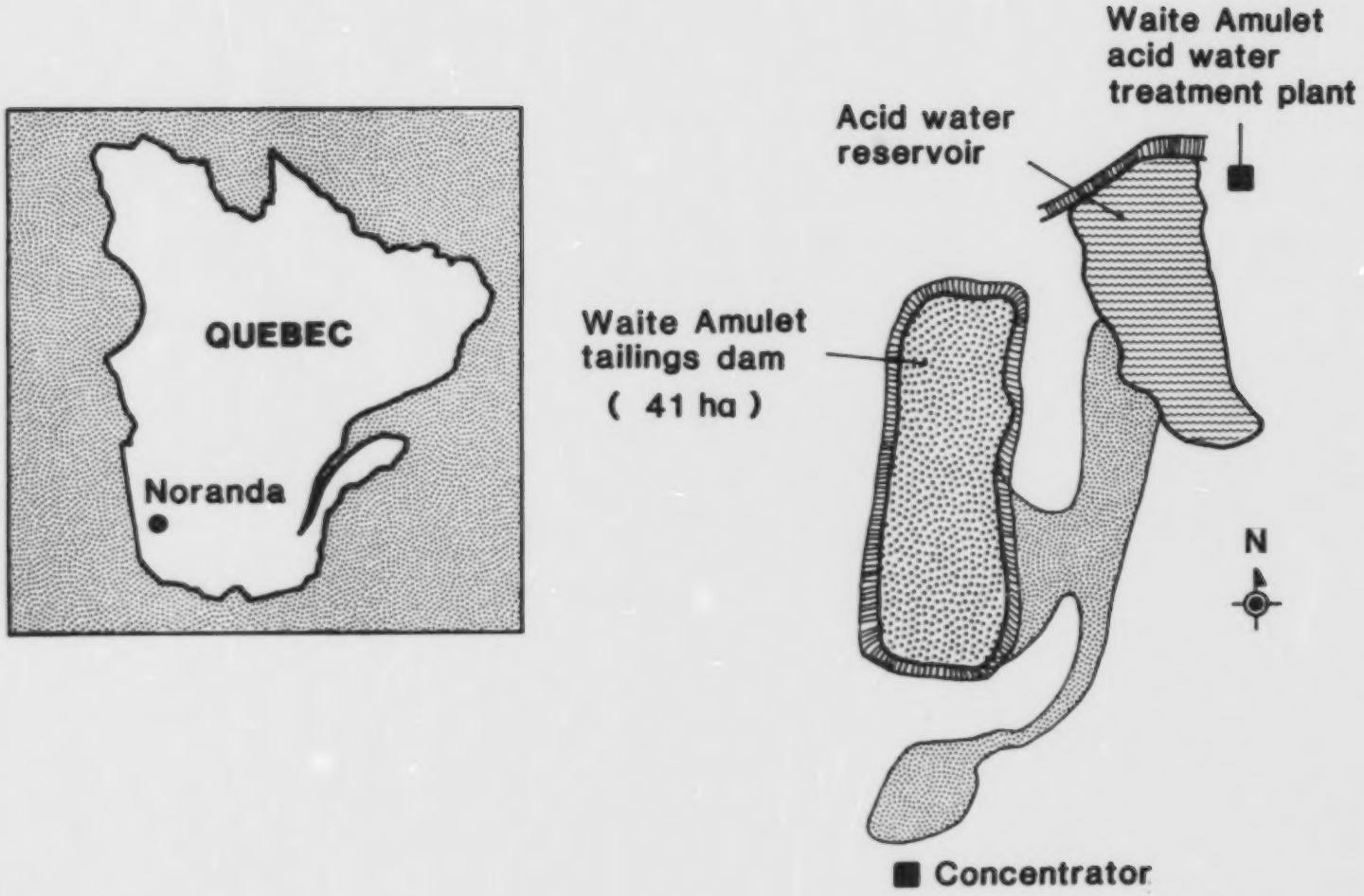


Figure 1 - Location of Waite Amulet Tailings

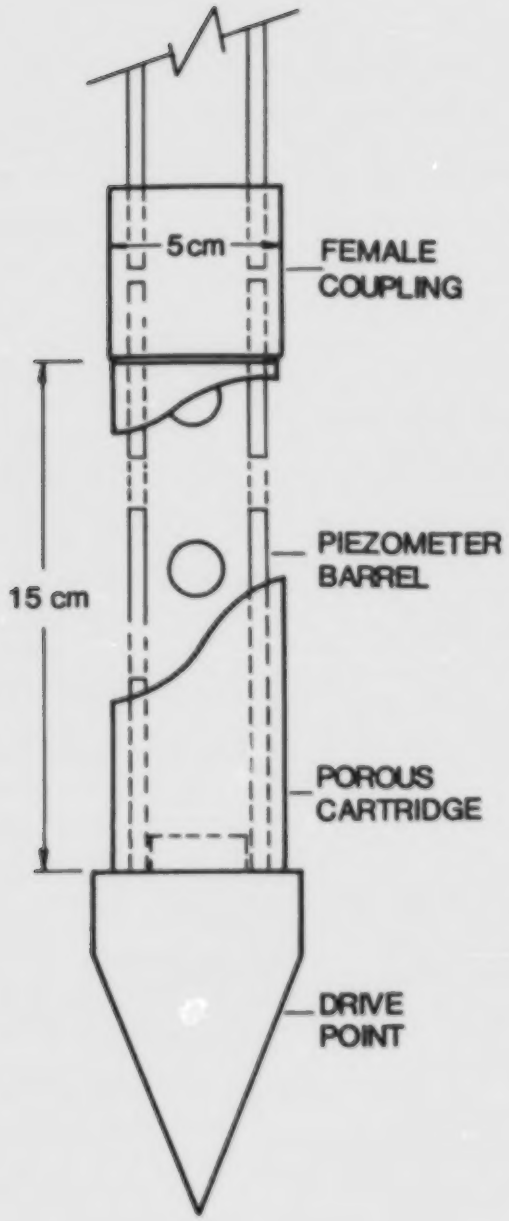
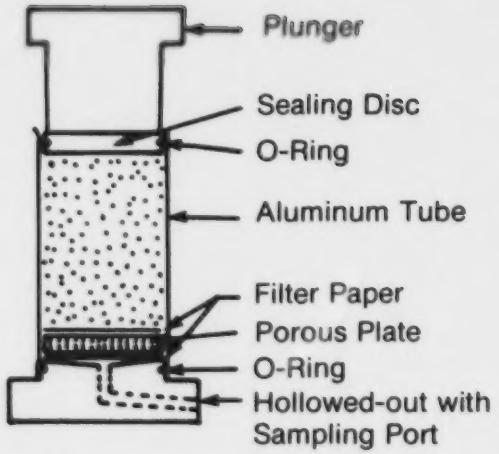


Figure 2 - Piezometer Tip

Squeezing Apparatus



Squeezing Apparatus and Stand

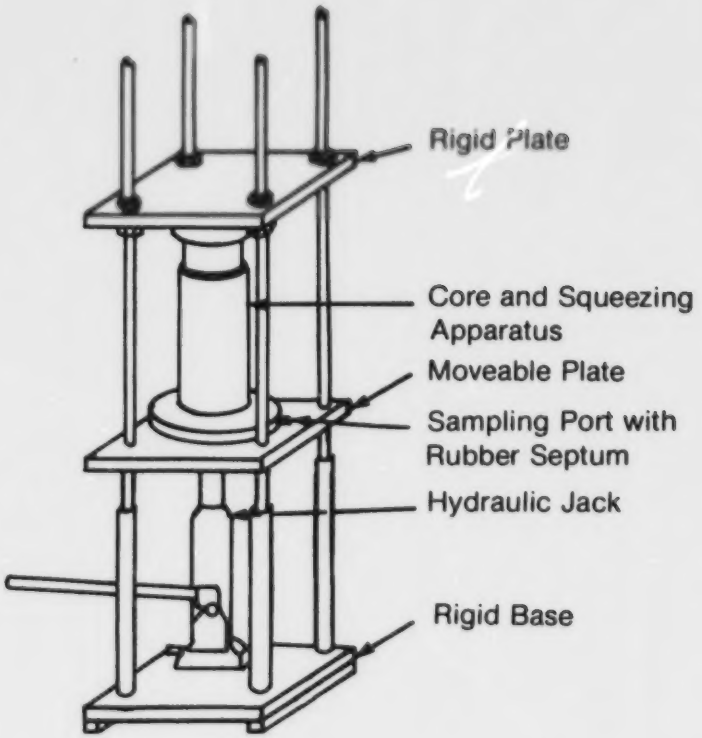


Figure 3 - Squeezing Apparatus for Unsaturated Zone Pore Water Extraction

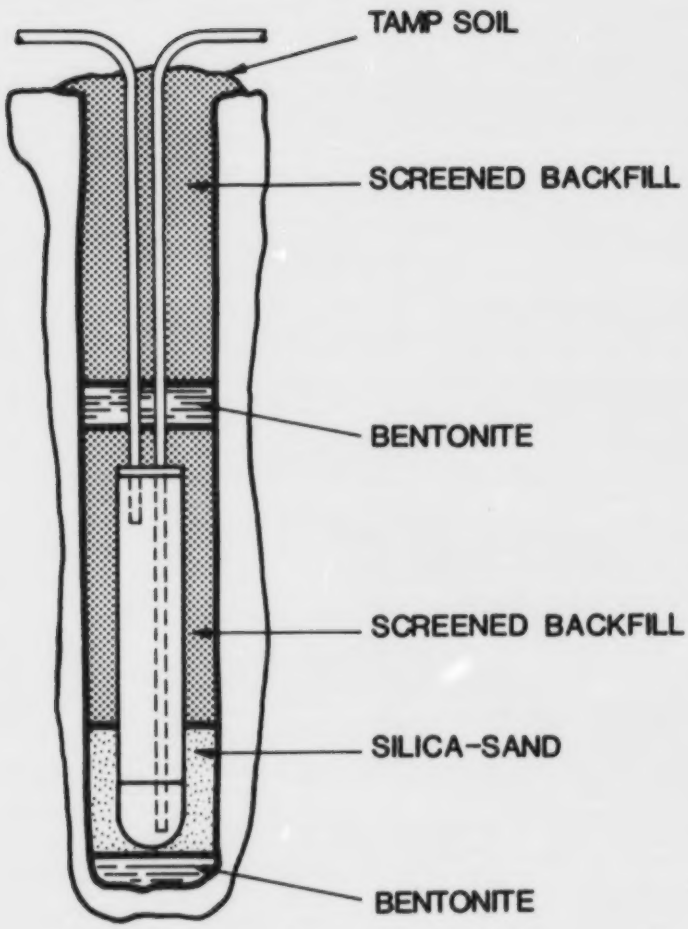


Figure 4 - Suction Lysimeter and Installation Method

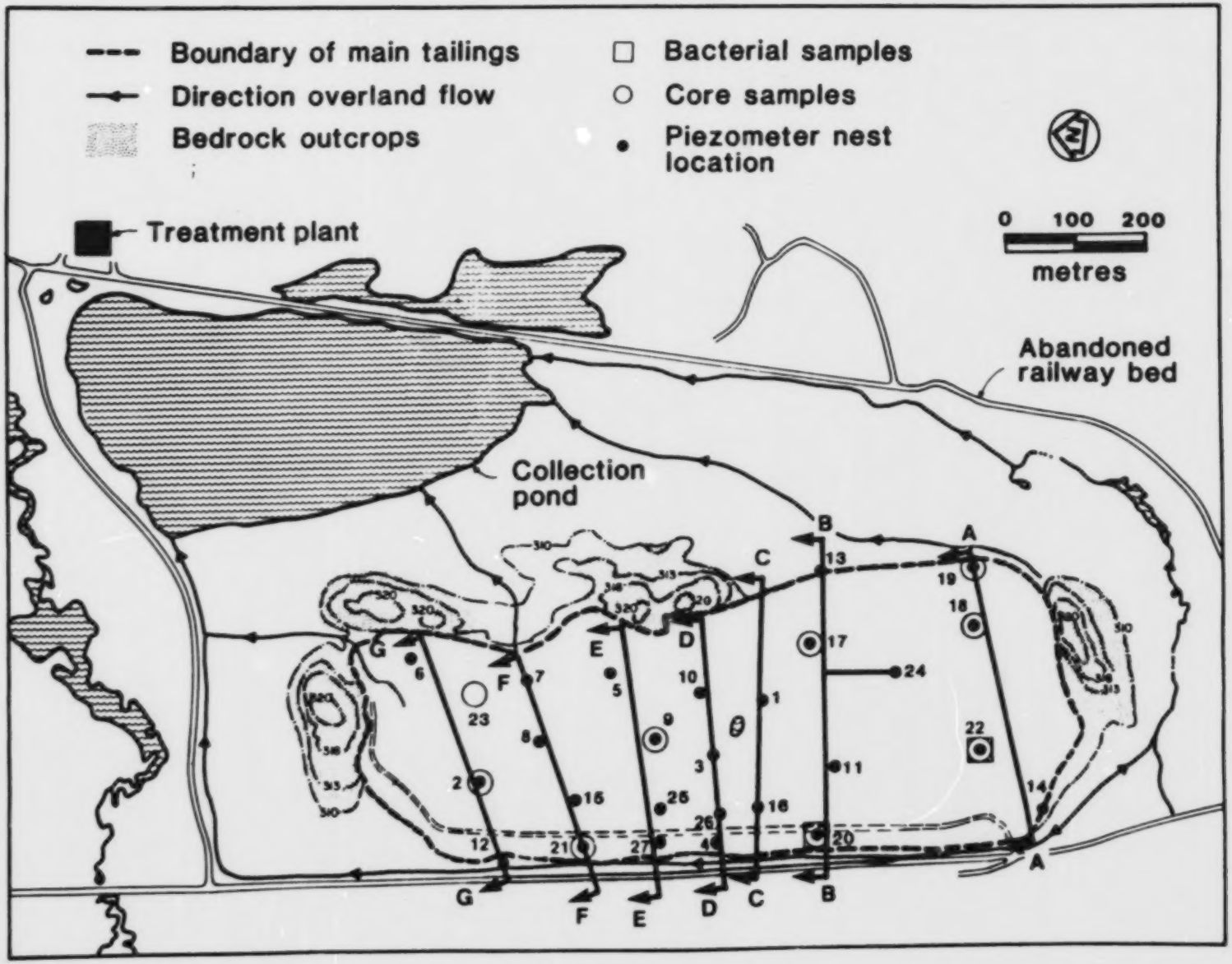


Figure 5 - Location of Piezometer Nests and Vertical Cross-Sections

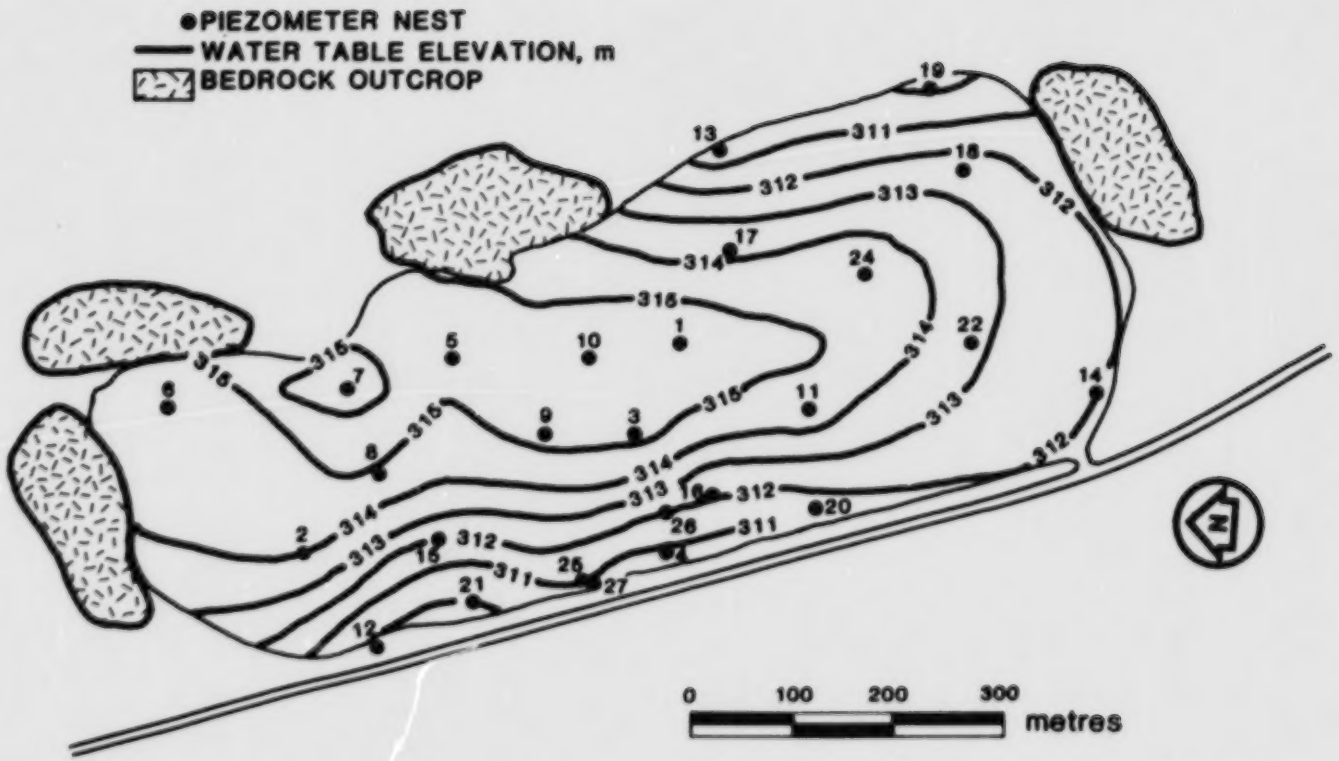


Figure 6 - Water Table at Waite Amulet, October 1986

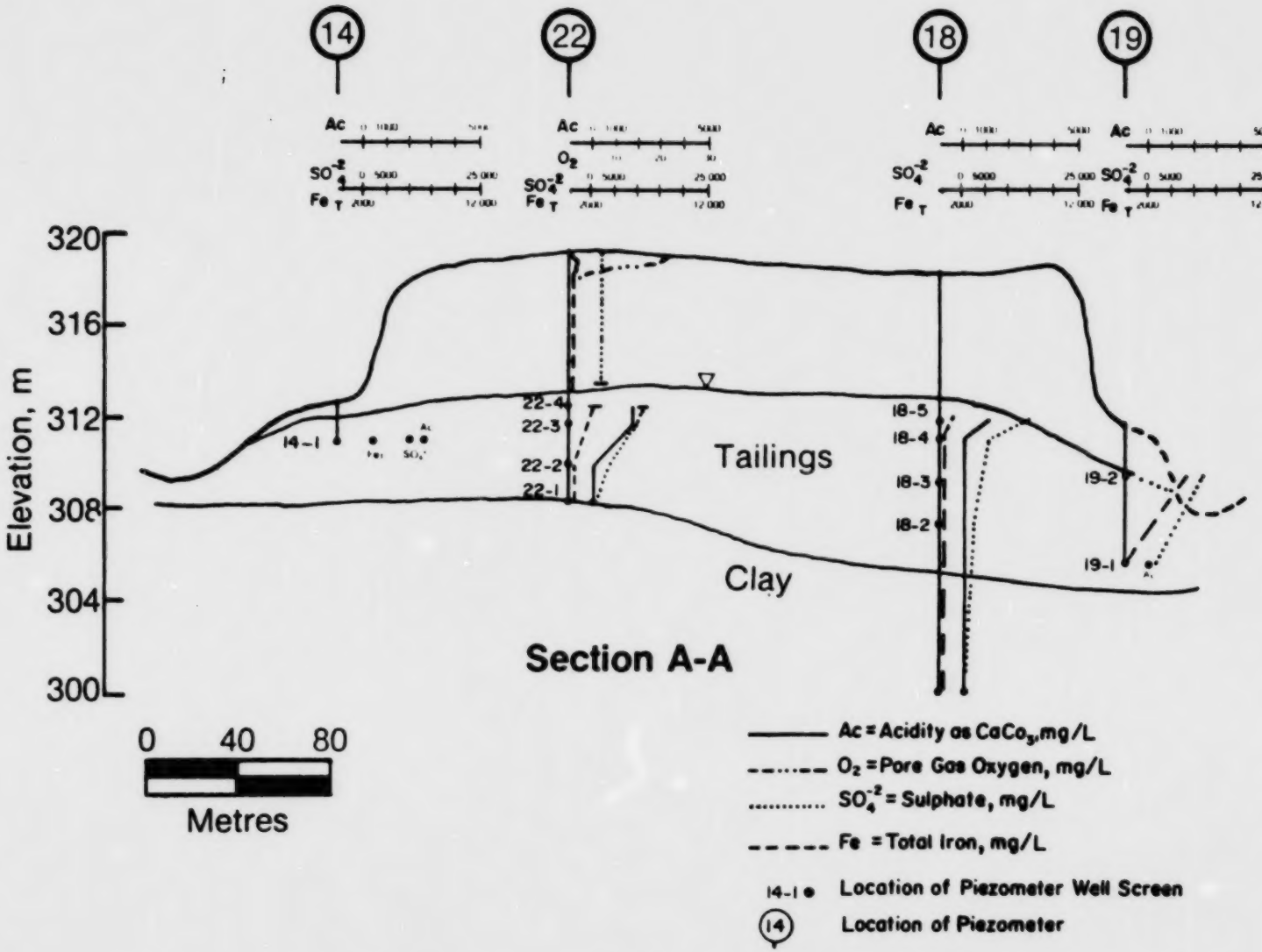


Figure 7 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section A-A

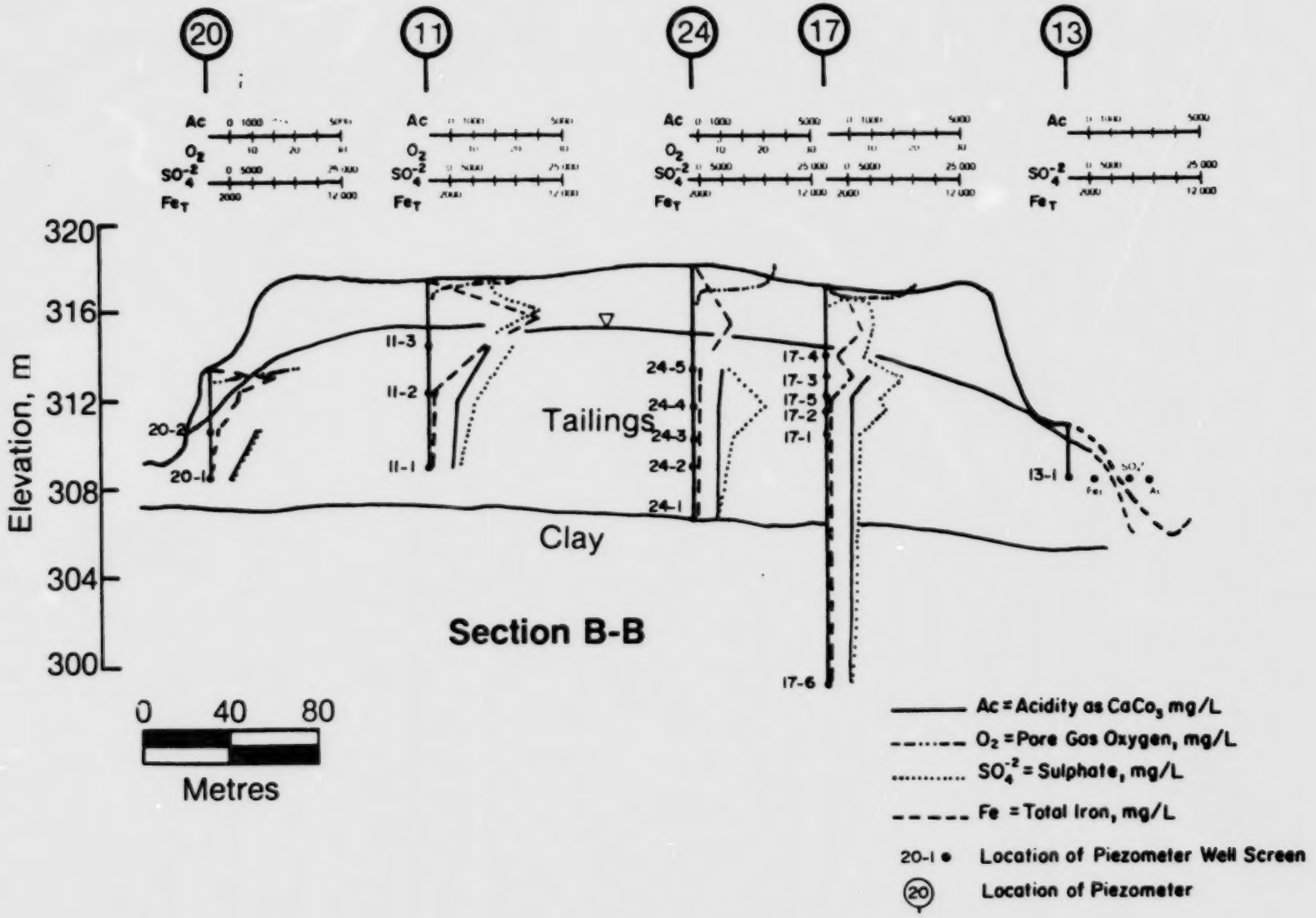


Figure 8 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section B-B

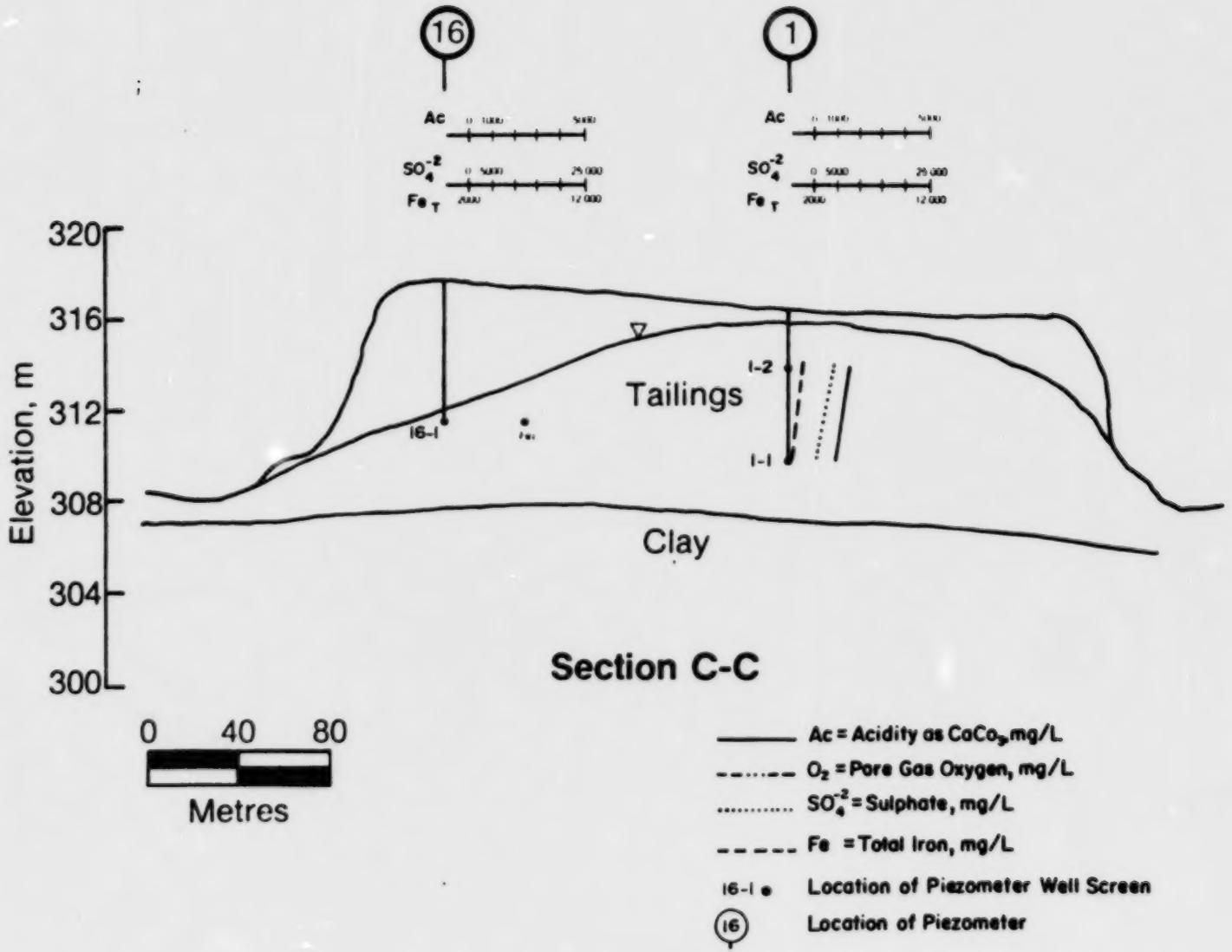


Figure 9 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section C-C

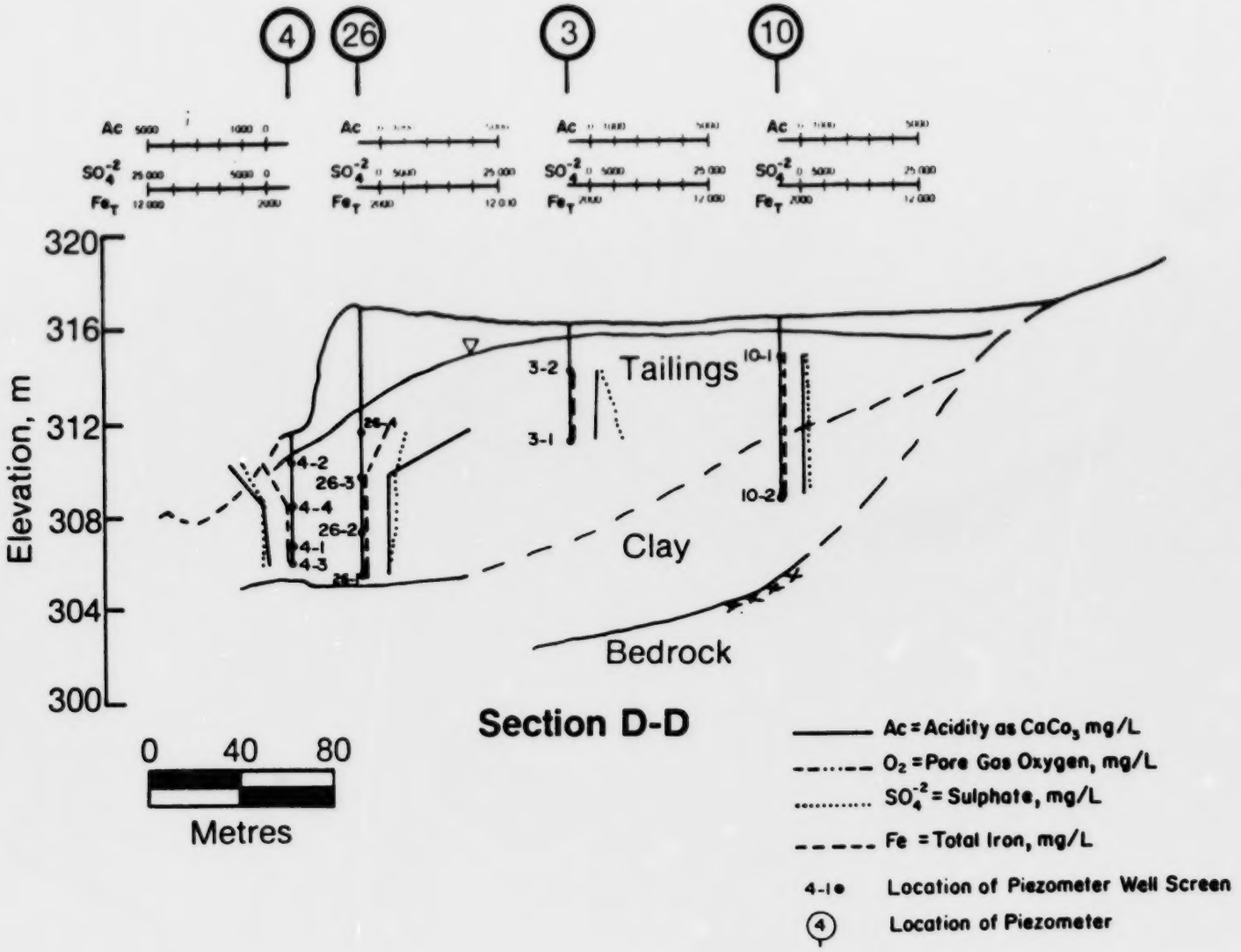


Figure 10 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section D-D

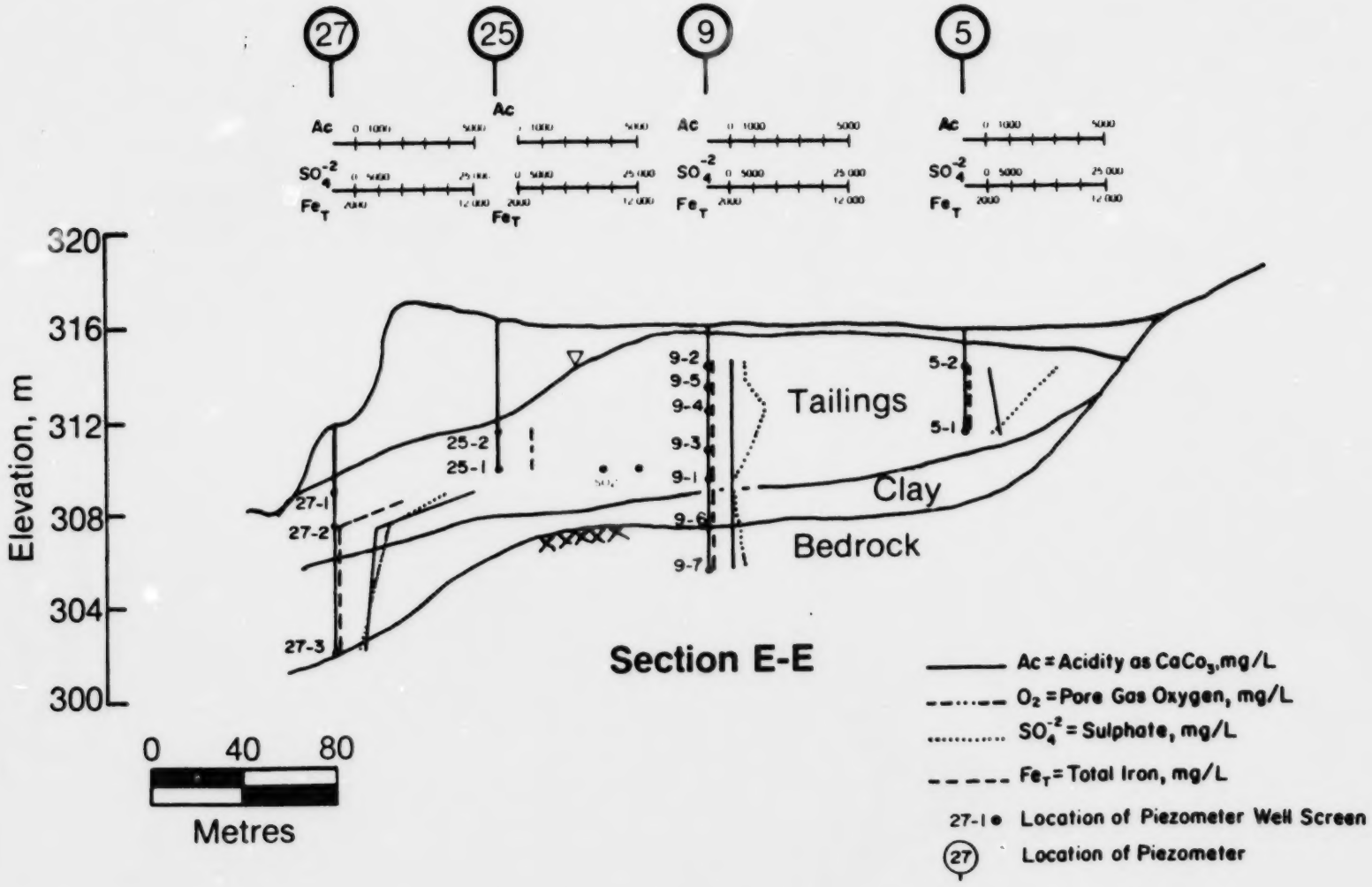


Figure 11 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section E-E

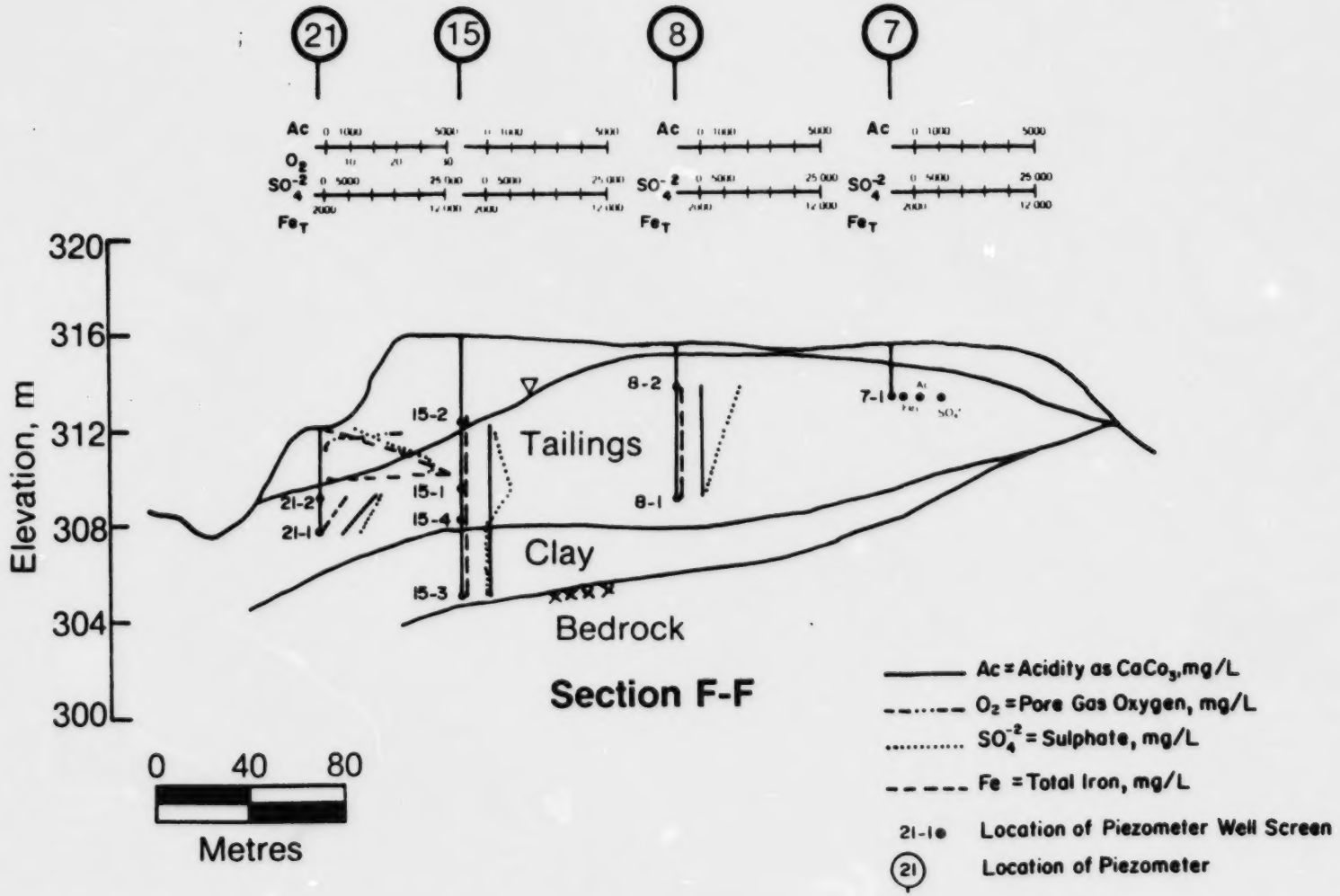


Figure 12 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section F-F

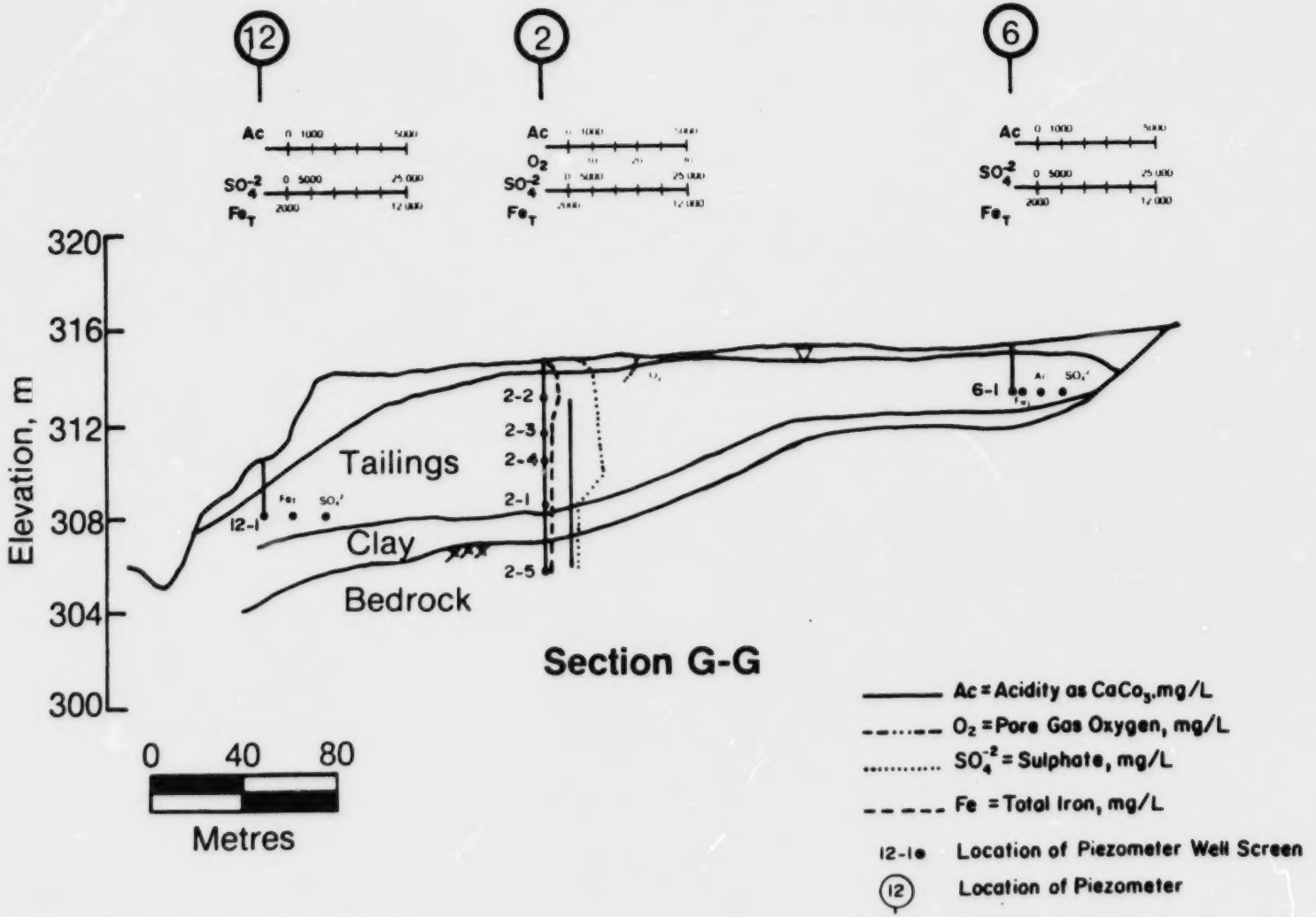


Figure 13 - Profiles of Fe_T, SO_4^{-2} and Acidity Concentrations in Pore Water and O_2 Concentration in Pore Gas Along Section G-G

TABLE I

TOTAL PROJECT TASK SCHEDULE AND CASH FLOW

	1985	1986	1987	1988	1989
1. Preliminary Reconnaissance Water table evaluation Geophysical survey Water analysis	—				
2. Preliminary Drilling Program Install piezometer nests Core samples Physical/chemical/bacterial core analysis	———				
3. Complete Drilling Program Install piezometer nests Core samples Physical/chemical/bacterial core analysis		———			
4. Monitor Surface Runoff Install flow recorders Install meteorological equipment		———	———	———	———
5. Data Acquisition Program Collection of water samples, flowrates and water elevation Data analysis and reporting	—	—	—	—	—
CASH FLOW ($,000)					
Noranda	50	115	35	40	35
CANMET	50	110	40	35	40
TOTAL:	100	225	75	75	75
(Cum. Total)	(100)	(325)	(400)	(475)	(550)

TABLE II

1986 PROJECT TASK SCHEDULE AND CASH FLOW PLAN

Task Description	Task Duration in Months											
	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July
1. FINALIZE HYDROGEOLOGY													
1.1 Piezometer Installation	———	———	———										
2. EVALUATE GEOCHEMISTRY													
2.1 Core Sampling	———	———	———	———									
2.2 Pore Gas Monitoring	———	———	———	———	———	———							
3. ASSESS OXIDATION CONTROL													
3.1 Meteorological Station	———	———	———	———									
3.2Flow Recorders	———	———	———	———									
3.3 Flownet Construction	———	———	———	———	———								
4. DATA ACQUISITION													
4.1 Sampling-Data Collection	———	———	———	———									
4.2 Water Analysis	———	———	———	———	———								
4.3 Data Processing	———	———	———	———	———	———							
4.4 Data Eval. · Reporting	———	———	———	———	———	———	———	———	———				
5. PROJECT MANAGEMENT	———	———	———	———	———	———	———	———	———				
Planned Cost by Month:	12	41	71	38	20	26	3	3	6				225
Actual													

Note: Costs are reported in $1,000/%
Project cost shared $115,000 Noranda, $110,000 DSS

TABLE III

QUALITY CONTROL OF ANALYTICAL RESULTS FOR WAITE AMULET PIEZOMETER WATER SAMPLES, OCTOBER 1986

	Co mg/L	Cu mg/L	Fe mg/L	Ni mg/L	Mg mg/L	Mn mg/L	Pb mg/L	Zn mg/L	Ca mg/L
Prepared High Metal Level Standard	10	0.3		0.5		5	1	1	
Laboratory Analysis	9.07	0.27		0.4		4.75	0.85	0.85	
	9.6	0.25		0.47		4.95	1.1	0.87	
	9.24	0.25		0.52		4.96	1.02	0.92	
	10.2	0.3		0.44		4.17	0.8	0.88	
	7.3	0.23		0.48		3.86	1.2	0.88	
$\bar{X}$	9.08	0.26		0.46		4.54	0.99	0.88	
S.D.	1.09	0.03		0.04		0.50	0.17	0.03	
C.V.	12	10		10		11	17	3	
R.E.	-9	-13		-8		-9	-1	-12	
Prepared Medium Metal Level Standard	1	0.1	50	0.1	50	1	0.5	0.1	50
Laboratory Analysis	0.85	0.06	52.2	<0.05	45	0.95	0.64	0.06	45
	1	0.02	51.9	<0.05	50	0.99	0.47	0.06	49
	0.97	0.02	47.1	<0.05	49	1.02	0.61	0.02	50
	1.02	0.02	50.2	<0.05	49	0.89	0.19	0.09	46
	1	0.08	47	<0.05	48	0.9	0.47	0.07	57
$\bar{X}$	0.97	0.04	49.68	0.05	48.20	0.95	0.48	0.06	49.40
S.D.	0.07	0.03	2.52	0.00	1.92	0.06	0.18	0.03	4.72
C.V.	7	71	5	0	4	6	37	42	10
R.E.	-3	-60	-1	-50	-4	-5	-5	-40	-1
Prepared Low Metal Level Standard	0.1	0.03	5	0.05	5	0.5	0.05	0.02	25
Laboratory Analysis	<0.05	<0.02	5	<0.05	6.5	0.42	<0.05	<0.01	27
	<0.05	<0.02	5.16	<0.05	5.2	0.44	<0.05	<0.01	27
	<0.05	<0.02	5.11	<0.05	3.8	0.45	<0.05	<0.01	25
	0.11	<0.02	5.1	<0.05	5	0.44	<0.05	<0.01	26
	0.09	<0.02	4.9	<0.05	4.1	0.39	<0.05	<0.01	26
$\bar{X}$	0.07	0.02	5.05	<0.05	4.92	0.43	<0.05	<0.01	26.20
S.D.	0.03	0	0.10	0	1.06	0.02	0	0	0.84
C.V.	40	0	2	0	22	6	0	0	3
R.E.	-30	-33	1	0	-2	-14	0	-50	5

$\bar{X}$ = Arithmetic mean
S.D. = Standard deviation
C.V. = Coefficient of variation
R.E. = Relative error

TABLE III (Cont'd)

QUALITY CONTROL OF ANALYTICAL RESULTS FOR WAITE AMULET PIEZOMETER WATER SAMPLES, OCTOBER 1986

	Co mg/l	Cu mg/l	Fe mg/l	Ni mg/l	Mg mg/l	Mn mg/l	Pb mg/l	Zn mg/l	Ca mg/l
Replicate 1	0.18	<0.02	1950	0.05	880	20.6	0.15	0.12	325
	0.15	<0.02	2005	0.09	940	21.1	0.11	0.08	375
	0.15	<0.02	2020	0.14	880	21.6	0.33	0.11	365
	0.11	<0.02	2020	0.14	820	21.2	0.22	0.07	385
	0.12	<0.02	2013	0.05	1010	20.6	0.18	0.08	365
$\bar{X}$	0.14	<0.02	2001.60	0.09	906.00	21.02	0.20	0.09	343.00
S.D.	0.03	0	29.50	0.05	71.97	0.43	0.08	0.02	22.80
C.V.	20	0	1	48	8	2	42	24	6
Replicate 2	<0.05	0.05	33	<0.05	61	0.66	<0.05	<0.01	485
	<0.05	<0.02	36	<0.05	64	0.66	<0.05	<0.01	595
	0.05	<0.02	34	<0.05	67	0.67	<0.05	<0.01	640
	<0.05	<0.02	32	<0.05	62	0.65	<0.05	<0.01	500
	<0.05	<0.02	33	<0.05	62	0.62	<0.05	<0.01	550
$\bar{X}$	<0.05	0.03	33.60	<0.05	63.20	0.65	<0.05	<0.01	554
S.D.	0	0.01	1.52	0	2.39	0.02	0	0	64.75
C.V.	0	52	5	0	4	3	0	0	12
Blank	<0.05	<0.02	<0.05	<0.05	<0.1	<0.02	<0.05	<0.01	<0.5
	<0.05	<0.02	<0.05	<0.05	<0.1	<0.02	<0.05	<0.01	<0.5
	<0.05	<0.02	<0.05	<0.05	<0.1	-	<0.05	<0.01	<0.5
	<0.05	<0.02	<0.05	<0.05	<0.1	<0.02	<0.05	<0.01	<0.5
Field Blank[1]	<0.05	<0.02	<0.05	<0.05	<0.1	<0.02	<0.05	<0.01	<0.5
	<0.05	<0.02	0.09	<0.05	<0.1	<0.02	<0.05	<0.01	<0.5

1. Field blanks were used to assess contamination from the sampling equipment by using distilled water which was pumped through the pumping unit and filters.

$\bar{X}$ = Arithmetic mean
S.D. = Standard deviation
C.V. = Coefficient of variation
R.E. = Relative error

TABLE IV

MICROSCOPIC OBSERVATIONS OF TEXTURE, ALTERATION FEATURE AND INTENSITY

Piezometer	Appendix C Reference Sample Number	Location	Texture Classification	Alteration of Intensity
2-1	A-1	Tailings-clay interface	Fine	Pyrrhotite/negligible
2-2	A-2	Tailings	Intermediate	/negligible
2-3	A-3	Tailings	Fine	Pyrrhotite/negligible
2-4	A-4	Tailings	Fine	/negligible
9-1	A-26	Tailings-clay interface	Intermediate	Pyrrhotite/negligible
9-2	A-27	Tailings	Intermediate	/negligible
9-3	A-28	Tailings	Fine	Pyrrhotite/negligible
9-4	A-29	Tailings	Fine	/negligible
9-5	A-30	Tailings	Fine	/negligible
9-6	A-31	Clay-rock interface	Fine	-
17-1	A-5	Tailings	Coarse to itermediate	Pyrrhotite/negligible
17-2	A-6	Tailings	Intermediate	/negligible
17-3	A-7	Tailings	Coarse to intermediate	/negligible
17-4	A-8	Tailings	Coarse to intermediate	/negligible
17-5	A-9	Tailings	Intermediate	/negligible
17-6	A-10	Clay	Clay	-
18-1	A-11	Clay	Clay	-
18-2	A-12	Tailings	Coarse	Pyrrhotite/negligible
18-3	A-13	Tailings	Coarse	Pyrrhotite/negligible
18-4	A-14	Tailings	Coarse	Pyrrhotite/negligible
18-5	A-15	Tailings	Coarse	Pyrrhotite/negligible
19-1	A-16	Tailings	Coarse	/negligible
19-2	A-17	Tailings	Coarse	Pyrrhotite/negligible
20-1	A-18	Tailings	Coarse	Pyrrhotite/negligible
20-2	A-19	Tailings	Coarse	Pyrrhotite/negligible
21-1	A-20	Tailings	Coarse	/negligible
21-2	A-21	Tailings	Coarse	/negligible
22-1	A-22	Tailings-clay interface	Intermediate	/negligible
22-2	A-23	Tailings	Intermediate	Pyrrhotite/negligible
22-3	A-24	Tailings	Intermediate	/negligible
22-4	A-25	Tailings	Coarse	/negligible

TABLE V

WAITE AMULET SATURATED TAILINGS POREWATER FIELD DETERMINED RESULTS AND ELEVATIONS

Piezo-meter	Date 1986	Elevation of Ground m	Well Screen Elevation m	Piezometer Water Level m	pH	Eh (mV)	Ec[1] (uS/cm)	Temp. °C	Acidity mg/L	Alkalinity mg/L
1-1	23 OCT.	316.50	309.93	315.31	7.86	409	1850	9	35.2	167.7
1-2	23 OCT.	316.46	313.98	315.99	6.29	277	2700	9	1761.8	48.8
2-1	23 OCT.	314.69	308.72	312.46	7.47	344			21.1	159.9
2-2	25 OCT.	314.75	313.23	314.39	5.67	394	4500	16		
2-3	23 OCT.	314.69	311.75	313.50	7.47	214	3600	8	37.0	195.0
2-4	23 OCT.	314.77	310.47	312.90	7.41	254	4500	8	14.1	138.5
2-5[2]	10 NOV.	314.70	305.91	311.56	6.43	289	2050	8	184.0	586.0
3-1	24 OCT.	316.18	311.31	315.23	7.55	361	4400	8	26.4	87.8
3-2	24 OCT.	316.18	314.21	315.72	6.54	294	1600	9	176.0	68.3
4-1	24 OCT.	309.57	306.73	309.02	6.26	342	1400	11	105.6	118.9
4-2	24 OCT.	311.49	310.28	310.51	4.51	444	4750	12	1760.0	17.6
4-3[2]	10 NOV.	311.49	306.12	310.22	6.86	213	1600	6	23.0	282.0
4-4	10 NOV.	311.49	308.52	310.27	6.31	215	1600	7	172.0	79.0
5-1	23 OCT.	315.76	311.35	315.52	6.61	309	1750	9	308.0	713.7
5-2	23 OCT.	315.75	314.05	315.22	7.55	214	5500	9	44.9	247.6
6-1		315.23	313.20	314.80	7.20	250	4850	14	82.7	538.2
7-1	23 OCT.	315.45	313.13	314.79	6.99	274	3690	9	225.3	126.8
8-1	23 OCT.	315.25	309.20	314.55	7.34	374	950	9	29.9	772.2
8-2	25 OCT.	315.37	313.83	315.30	7.01	333	5500	14	172.5	263.3
9-1	25 OCT.	316.05	309.38	314.65	7.38	304	950	9	52.8	733.2
9-2	25 OCT.	316.07	314.44	315.76	7.11	264	2050	10	56.3	48.8
9-3	25 OCT.	316.07	310.88	314.95	7.84	312	3050	6	14.1	136.5
9-4	25 OCT.	316.07	312.55	315.56	7.36	304	4500	10	95.0	64.4
9-5	25 OCT.	316.06	313.64	315.63	6.95	294	2150	9	26.4	93.6
9-6	25 OCT.	316.09	307.43	314.11	7.39	291	2620	11	26.4	403.7
9-7[2]	10 NOV.	316.10	305.71	314.15	6.47	320	2800	8	92.0	327.0
10-1	25 OCT.	316.42	308.93	315.44	7.61	354	1100	16	24.6	965.3
10-2	25 OCT.	316.32	308.91	315.49	6.20	385	1400	14	299.2	29.3
11-1	24 OCT.	317.31	308.99	313.96	7.94	205	2350		12.3	101.4
11-2	24 OCT.	317.38	312.29	314.44	6.80	233	3800		281.6	146.3
11-3	24 OCT.	317.33	314.40	314.87	4.30	454	6000	11	1760.0	
12-1		310.68	308.19	309.64	5.84	326	5000	14		25.4
13-1	25 OCT.	310.73	308.14	310.28	6.12	299	4500	13	2640.0	29.3
14-1	25 OCT.	312.55	310.82	312.01	5.30	376	7000	15	2640.0	9.8
15-1	24 OCT.	315.91	309.48	311.53	7.07	293	3450	9	52.8	76.1
15-2	24 OCT.	315.90	312.50	312.35						
15-3[2]	10 NOV.	315.90	304.94	311.71	7.15	392	750	4	46.0	710.0
15-4[2]	10 NOV.	315.90	308.11	311.42	6.94	236	1000		104.0	676.0
16-1	25 OCT.	317.87	311.75	311.84	3.67	489				
17-1	23 OCT.	317.07	310.32	313.66	7.56	334	2300	6	29.9	60.5
17-2	23 OCT.	317.09	311.46	313.82	7.06	349	4000	6	19.4	126.8
17-3	23 OCT.	317.06	312.93	313.82	6.13	324	4850	6	880.0	33.2
17-4	25 OCT.	317.03	313.79	313.81	5.81	348	3900	14		
17-5	23 OCT.	317.05	311.75	313.75	7.58	284	3750	6	37.8	
17-6	23 OCT.	317.34	298.93	310.59	7.86	299	600		26.4	302.3
18-1	24 OCT.	318.25	300.20	310.82	7.78	294	890	10	17.6	424.1
18-2	24 OCT.	318.19	307.35	312.52	5.76	372	1860	8	26.4	19.5
18-3	24 OCT.	318.20	309.12	312.55	7.43	264	2500	8	49.3	83.9
18-4	24 OCT.	318.18	311.12	312.60	7.26	254	3000	11	167.2	132.6
18-5	24 OCT.	318.17	311.91	312.62	6.27	254	2850	10	1080.6	50.7
19-1	24 OCT.	311.58	305.68	309.59	7.40	234	1450	8	50.2	294.5
19-2	24 OCT.	311.56	309.57	309.56	3.59	434	4280	5		
20-1	24 OCT.	313.42	308.43	311.19	7.62	272	1000	11	17.6	678.6
20-2	24 OCT.	313.43	310.60	311.23	6.38	259	4350	11	1012.0	97.5
21-1	24 OCT.	312.07	307.65	309.78	7.51	287	2350	9	26.4	207.7
21-2	24 OCT.	312.05	309.07	309.79	5.92	305	4000	9	1760.0	15.6
22-1	24 OCT.	319.26	308.25	309.48	6.95	231	1600	11	161.0	661.1
22-2	24 OCT.	319.26	309.99	313.27	7.45	203	2700	11	79.2	195.0
22-3	24 OCT.	319.21	311.60	313.23	6.05	265	4500	11	1760.0	42.9
22-4	24 OCT.	319.20	312.24	313.23	5.94	262	4720	11	1760.0	72.2
24-1[2]	10 NOV.	318.20	306.64	314.23	9.53	438	1050	7		316.0
24-2[2]	10 NOV.	318.20	308.79	314.25	7.80	460	2100	7	23.0	135.0
24-3[2]	10 NOV.	318.20	310.20	314.45	7.17	232	3400	7	35.0	68.0
24-4[2]	10 NOV.	318.20	311.67	314.78	7.40	159	6200	12	92.0	169.0
24-5[2]	10 NOV.	318.20	313.26	314.96	6.66	215	3200	12	207.0	34.0
25-1[2]	10 NOV.	316.50	310.01	311.22	5.92	217	10000	8	5350.0	79.0
25-2[2]	10 NOV.	316.50	311.63	311.56						
26-1[2]	10 NOV.	317.00	305.40	311.67	7.20	449	650	5	11.0	394.0
26-2[2]	10 NOV.	317.00	307.25	311.82	7.66	153	2300	6	11.0	180.0
26-3[2]	10 NOV.	317.00	309.87	312.11	6.74	158	1450	7	69.0	45.0
26-4[2]	10 NOV.	317.00	311.72	312.50	5.32	292	3800	8	3690.0	23.0
27-1[2]	10 NOV.	312.00	302.18	309.12	6.29	263	340	13	58.0	248.0
27-2[2]	10 NOV.	312.01	307.75	309.81	6.03	258	7000	12	943.0	124.0
27-3[2]	10 NOV.	312.00	309.06	309.76	5.27	314	1100	8	1300.0	56.0

1. Non-standardized
2. Estimated elevations

TABLE VI

WAITE AMULET SATURATED ZONE TAILINGS POREWATER ION CONCENTRATIONS

Piezo-meter	Date 1986	Fe^{+2}* mg/L	Fe_T mg/L	Al mg/L	Co mg/L	Cu mg/L	Mn mg/L	Cd mg/L	Cr mg/L	Ni mg/L	Pb mg/L	Zn mg/L
1-1	23 OCT.	<1.1	0.37	<2.5	0.13	<0.02	0.11	<0.005	<0.05	<0.05	<0.05	0.02
1-2	23 OCT.	1332.0	1110.00	<2.5	0.12	<0.02	13.00	<0.005	<0.05	<0.05	<0.05	0.06
2-1	23 OCT.	24.0	2.80	<2.5	<0.05	<0.02	0.27	<0.005	<0.05	<0.05	<0.05	<0.01
2-2	25 OCT.	1530.0	1100.00	<2.5	<0.05	0.17	41.20	<0.005	<0.05	<0.05	0.11	1.49
2-3	23 OCT.	24.0	17.30	<2.5	<0.05	<0.02	1.27	<0.005	<0.05	<0.05	0.07	0.03
2-4	23 OCT.	12.0	14.30	<2.5	<0.05	<0.02	1.23	<0.005	<0.05	<0.05	0.11	<0.01
2-5	10 NOV.	14.0	9.60	<1.0	<0.05	<0.02	21.00	<0.005	<0.05	<0.05	<0.05	0.11
3-1	24 OCT.	12.0	80.00	<2.5	<0.05	<0.02	1.63	<0.005	<0.05	<0.05	<0.05	<0.01
3-2	24 OCT.	96.0	17.80	<2.5	<0.05	<0.02	0.27	<0.005	<0.05	<0.05	<0.05	<0.01
4-1	24 OCT.	36.0	0.27	130.00	0.39	<0.02	24.80	<0.005	<0.05	0.09	0.18	15.50
4-2	24 OCT.	3246.0	2610.00	<2.5	0.08	<0.02	0.05	<0.005	<0.05	<0.05	<0.05	<0.01
4-3	10 NOV.	4.4	2.30	<1.0	<0.05	<0.02	0.16	<0.005	<0.05	<0.05	<0.05	<0.01
4-4	10 NOV.	80.0	71.00	<1.0	<0.05	<0.02	0.63	<0.005	<0.05	<0.05	<0.05	<0.01
5-1	23 OCT.	150.0	143.00	<2.5	<0.05	<0.02	6.42	<0.005	0.18	<0.05	0.07	<0.01
5-2	23 OCT.	36.0	24.40	<2.5	0.08	<0.02	1.83	0.01	0.07	0.06	<0.05	0.03
6-1		12.0	5.93	<2.5	<0.05	<0.02	8.40	<0.005	0.09	<0.05	<0.05	<0.01
7-1	23 OCT.	156.0	125.00	<2.5	<0.05	<0.02	2.13	<0.005	0.06	<0.05	<0.05	0.01
8-1	23 OCT.	<1.1	<0.05	<2.5	<0.05	<0.02	0.26	<0.005	<0.05	<0.05	<0.05	0.02
8-2	25 OCT.	96.0	75.00	<2.5	<0.05	<0.02	0.22	<0.005	<0.05	<0.05	<0.05	0.01
9-1	25 OCT.	6.0	8.85	<2.5	<0.05	<0.02	0.36	<0.005	<0.05	<0.05	<0.05	<0.01
9-2	25 OCT.	24.0	21.10	<2.5	<0.05	<0.02	1.44	<0.005	<0.05	<0.05	<0.05	0.06
9-3	25 OCT.	12.0	2.70	<2.5	<0.05	<0.02	0.32	<0.005	<0.05	<0.05	<0.05	<0.01
9-4	25 OCT.	36.0	12.20	<2.5	0.07	<0.02	1.30	<0.005	<0.05	<0.05	<0.05	<0.01
9-5	25 OCT.	12.0	6.41	<2.5	<0.05	<0.02	0.82	<0.005	<0.05	<0.05	<0.05	<0.01
9-6	25 OCT.	24.0	13.50	<2.5	<0.05	<0.02	9.81	<0.005	<0.05	<0.05	<0.05	<0.01
9-7	10 NOV.	4.4	3.70	<1.0	<0.05	<0.02	16.00	<0.005	<0.05	<0.05	<0.05	<0.01
10-1	25 OCT.	6.0	9.93	<2.5	<0.05	<0.02	1.21	<0.005	<0.05	<0.05	<0.05	<0.01
10-2	25 OCT.	180.0	130.00	<2.5	<0.05	<0.02	2.55	<0.005	<0.05	<0.05	<0.05	<0.01
11-1	24 OCT.	12.0	0.95	<2.5	<0.05	<0.02	0.12	<0.005	<0.05	<0.05	<0.05	<0.01
11-2	24 OCT.	144.0	112.00	<2.5	<0.05	<0.02	3.47	<0.005	<0.05	<0.05	<0.05	<0.01
11-3	24 OCT.	6048.0	5570.00	<2.5	0.33	<0.02	79.30	0.03	<0.05	0.11	0.36	0.19
12-1		2640.0	2255.00	<2.5	0.21	<0.02	25.30	0.01	<0.05	0.05	0.07	0.07
13-1	25 OCT.	2280.0	2002.00	<2.5	0.14	<0.02	21.00	<0.005	<0.05	0.11	0.20	0.09
14-1	25 OCT.	3816.0	3343.00	<2.5	0.24	<0.02	44.10	0.04	<0.05	0.11	0.36	0.28
15-1	24 OCT.	12.0	9.43	<2.5	<0.05	<0.02	1.62	<0.005	<0.05	<0.05	<0.05	<0.01
15-2	24 OCT.			<2.5	<0.05	<0.02		<0.005	<0.05	<0.05	<0.05	<0.01
15-3	10 NOV.	<1.1	<0.05	<1.0	<0.05	<0.02	0.52	<0.005	<0.05	<0.05	<0.05	<0.01
15-4	10 NOV.	16.0	10.70	<1.0	<0.05	<0.02	0.30	<0.005	<0.05	<0.05	<0.05	<0.01
16-1	25 OCT.		7280.00	<2.5	0.13	0.55	62.00	0.04	<0.05	0.11	0.30	2.07
17-1	23 OCT.	<1.1	7.11	<2.5	<0.05	<0.02	0.93	<0.005	<0.05	<0.05	<0.05	<0.01
17-2	23 OCT.	<1.1	17.70	<2.5	<0.05	<0.02	2.20	<0.005	<0.05	<0.05	<0.05	<0.01
17-3	23 OCT.	2820.0	2400.00	<2.5	<0.05	<0.02	29.90	<0.005	0.08	<0.05	<0.05	0.12
17-4	25 OCT.		1020.00	<2.5	<0.05	<0.02	13.40	<0.005	<0.05	<0.05	<0.05	0.25
17-5	23 OCT.	18.0	18.80	<2.5	<0.05	<0.02	2.10	<0.005	<0.05	<0.05	<0.05	<0.01
17-6	23 OCT.	<1.1	0.74	<2.5	<0.05	<0.02	0.52	<0.005	<0.05	<0.05	<0.05	<0.01
18-1	24 OCT.	<1.1	0.08	<2.5	<0.05	<0.02	0.95	<0.005	<0.05	<0.05	<0.05	<0.01
18-2	24 OCT.	60.0	0.37	<2.5	<0.05	<0.02	1.12	<0.005	<0.05	<0.05	<0.05	<0.01
18-3	24 OCT.	36.0	21.80	<2.5	<0.05	<0.02	1.06	<0.005	<0.05	<0.05	<0.05	0.13
18-4	24 OCT.	84.0	69.00	<2.5	<0.05	<0.02	1.55	<0.005	<0.05	<0.05	0.07	<0.01
18-5	24 OCT.	780.0	625.00	<2.5	0.05	<0.02	4.92	0.01	0.05	<0.05	<0.05	0.05
19-1	24 OCT.	24.0	22.60	<2.5	<0.05	<0.02	0.73	<0.005	<0.05	<0.05	<0.05	<0.01
19-2	24 OCT.		4500.00	20.00	<0.05	0.14	27.20	0.01	<0.05	0.28	<0.05	21.80
20-1	24 OCT.	12.0	2.18	<2.5	<0.05	<0.02	0.34	<0.005	<0.05	<0.05	<0.05	<0.01
20-2	24 OCT.	696.0	525.00	<2.5	<0.05	<0.02	5.64	<0.005	<0.05	<0.05	<0.05	<0.01
21-1	24 OCT.	12.0	5.89	<2.5	<0.05	<0.02	0.06	<0.005	<0.05	<0.05	<0.05	<0.01
21-2	24 OCT.	2496.0	2030.00	<2.5	0.07	<0.02	21.40	<0.005	<0.05	<0.05	<0.05	0.04
22-1	24 OCT.	54.0	45.50	<2.5	<0.05	<0.02	0.21	<0.005	<0.05	<0.05	<0.05	<0.01
22-2	24 OCT.	24.0	27.10	<2.5	<0.05	<0.02	0.66	<0.005	<0.05	<0.05	<0.05	<0.01
22-3	24 OCT.	2040.0	1680.00	<2.5	<0.05	<0.02	15.00	0.01	<0.05	<0.05	<0.05	<0.01
22-4	24 OCT.	2520.0	2145.00	<2.5	<0.05	<0.02	19.30	<0.005	<0.05	<0.05	0.08	<0.01
24-1	10 NOV.	<1.1	<0.05	<1.0	<0.05	<0.02	0.03	<0.005	<0.05	<0.05	<0.05	<0.01
24-2	10 NOV.	<1.1	<0.05	<1.0	<0.05	<0.02	0.09	<0.005	<0.05	<0.05	<0.05	<0.01
24-3	10 NOV.	3.4	2.10	<1.0	<0.05	<0.02	0.42	<0.005	<0.05	<0.05	<0.05	<0.01
24-4	10 NOV.	19.0	10.00	<1.0	0.07	<0.02	1.66	<0.005	<0.05	<0.05	<0.05	0.07
24-5	10 NOV.	131.0	115.00	<1.0	<0.05	<0.02	1.40	<0.005	<0.05	<0.05	<0.05	0.13
25-1	10 NOV.	3130.0	2550.00	<1.0	0.15	<0.02	25.20	0.02	0.06	<0.05	<0.05	0.40
25-2	10 NOV.		2365.00	5.00	0.11	<0.02	24.40	0.02	0.26	0.06	0.19	3.00
26-1	10 NOV.	<1.1	<0.05	<1.0	<0.05	<0.02	<0.02	0.02	<0.05	<0.05	<0.05	<0.01
26-2	10 NOV.	2.2	0.15	<1.0	<0.05	<0.02	0.09	<0.005	<0.05	<0.05	<0.05	<0.01
26-3	10 NOV.	44.0	33.60	<1.0	<0.05	<0.02	0.65	<0.005	<0.05	<0.05	<0.05	<0.01
26-4	10 NOV.	2150.0	1840.00	<1.0	0.07	<0.02	10.00	<0.005	0.26	<0.05	0.09	1.40
27-1	10 NOV.	<1.1	<0.05	<1.0	<0.05	<0.02	0.30	<0.005	<0.05	<0.05	<0.05	<0.01
27-2	10 NOV.	476.0	320.00	<1.0	<0.05	<0.02	3.10	<0.005	0.17	<0.05	<0.05	0.18
27-3	10 NOV.	7760.0	6955.00	27.00	0.24	<0.02	85.00	<0.005	0.39	<0.05	<0.05	0.25

* Field determined

TABLE VI (Cont'd)
WAITE AMULET SATURATED ZONE TAILINGS POREWATER ION CONCENTRATIONS

Piezo-meter	Date 1986	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	SO_4^{-2} mg/L	Cl mg/L
1-1	23 OCT.	525	65.0	390.0	14.6	1250	
1-2	23 OCT.	100	45.0	28.0	470.0	4750	
2-1	23 OCT.	414	55.0	1360.0	32.0	1200	
2-2	25 OCT.	320	14.0	640.0	25.0	5200	
2-3	23 OCT.	540	90.0	1670.0	240.0	5750	
2-4	23 OCT.	425	95.0	970.0	490.0	7000	
2-5	10 NOV.	475	3.1	155.0	270.0	1800	
3-1	24 OCT.	446	38.0	91.0	7.3	5650	
3-2	24 OCT.	110	17.0	13.7	355.0	1600	
4-1	24 OCT.	410	27.0	320.0	6.3	1000	14.0
4-2	24 OCT.	50	67.0	395.0	580.0	6750	2.3
4-3	10 NOV.	66	42.0	62.0	380.0	1200	
4-4	10 NOV.	595	11.0	37.0	5.6	1650	
5-1	23 OCT.	350	32.0	145.0	245.0	1700	
5-2	23 OCT.	410	155.0	3040.0	140.0	14000	
6-1		470	47.0	865.0	115.0	5000	
7-1	23 OCT.	420	80.0	1220.0	33.0	6200	
8-1	23 OCT.	47	20.0	32.0	290.0	110	
8-2	25 OCT.	46	19.0	31.0	280.0	7600	
9-1	25 OCT.	56	26.0	36.0	290.0	275	16.0
9-2	25 OCT.	460	62.0	305.0	12.0	2500	8.5
9-3	25 OCT.	120	90.0	150.0	770.0	3400	25.0
9-4	25 OCT.	530	95.0	1310.0	405.0	6800	28.0
9-5	25 OCT.	375	78.0	485.0	27.0	2900	27.0
9-6	25 OCT.	65	43.0	565.0	680.0	1825	25.0
9-7	10 NOV.	250	8.8	75.0	775.0	2300	
10-1	25 OCT.	62	16.0	41.0	290.0	34	
10-2	25 OCT.	435	16.0	12.0	3.6	1500	
11-1	24 OCT.	77	85.0	70.0	720.0	1950	16.0
11-2	24 OCT.	410	130.0	940.0	940.0	6000	34.0
11-3	24 OCT.	435	80.0	905.0	10.0	13000	
12-1		435	65.0	705.0	14.0	8200	
13-1	25 OCT.	363	85.0	906.0	40.0	8825	
14-1	25 OCT.	364	65.0	960.0	50.0	10750	
15-1	24 OCT.	445	87.0	800.0	70.0	4700	
15-2	24 OCT.						
15-3	10 NOV.	160	3.3	57.0	43.0	39	
15-4	10 NOV.	96	12.0	68.0	185.0	115	
16-1	25 OCT.	405	52.0	870.0	28.0		
17-1	23 OCT.	250	95.0	130.0	610.0	2850	
17-2	23 OCT.	385	170.0	1700.0	42.0	8400	
17-3	23 OCT.	425	160.0	1360.0	23.0	12750	
17-4	25 OCT.	370	55.0	190.0	7.6	4400	
17-5	23 OCT.	360	160.0	1310.0	24.0	7200	
17-6	23 OCT.	79	3.8	26.0	43.0	143	
18-1	24 OCT.	145	5.0	46.2	140.0	500	7.0
18-2	24 OCT.	485	49.0	150.0	230.0	2600	9.0
18-3	24 OCT.	445	57.0	655.0	47.0	4000	14.0
18-4	24 OCT.	410	80.0	840.0	26.0	5300	34.0
18-5	24 OCT.	505	50.0	625.0	17.0	14600	14.0
19-1	24 OCT.	270	45.0	160.0	275.0	1700	7.0
19-2	24 OCT.	350	20.0	275.0	12.0	11000	
20-1	24 OCT.	29	25.0	9.6	405.0	195	26.0
20-2	24 OCT.	400	100.0	1135.0	22.0	7200	9.0
21-1	24 OCT.	125	58.0	185.0	475.0	2400	
21-2	24 OCT.	335	90.0	410.0	16.0	7500	
22-1	24 OCT.	285	22.0	94.0	235.0	1150	9.0
22-2	24 OCT.	460	59.0	395.0	140.0	3400	11.0
22-3	24 OCT.	460	70.0	840.0	23.0	8500	82.0
22-4	24 OCT.	420	64.0	795.0	16.0	9500	61.0
24-1	10 NOV.	4	23.0	0.3	330.0	400	
24-2	10 NOV.	91	67.0	45.0	550.0	1700	
24-3	10 NOV.	640	69.0	487.0	170.0	3900	
24-4	10 NOV.	475	123.0	2150.0	37.0	11200	
24-5	10 NOV.	460	50.0	435.0	18.0	3200	
25-1	10 NOV.	360	130.0	1583.0	445.0	17000	
25-2	10 NOV.	325	46.0	300.0	13.0		
26-1	10 NOV.	24	10.0	14.0	185.0	<1.00	120.0
26-2	10 NOV.	73	42.0	60.0	570.0	1650	
26-3	10 NOV.	613	29.0	63.0	7.8	1620	
26-4	10 NOV.	440	37.0	108.0	5.2	4500	
27-1	10 NOV.	71	2.2	14.0	32.0	96	
27-2	10 NOV.	370	86.0	1065.0	270.0	6400	
27-3	10 NOV.	395	37.0	1030.0	15.0	18750	

APPENDIX A

Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

With Regards
W. Petruk

MINERALOGICAL AND IMAGE ANALYSIS STUDY OF SAMPLES FROM CORE WA20 OF THE WAITE AMULET TAILINGS

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Mineral Processing Laboratory

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MINERALOGICAL AND IMAGE ANALYSIS STUDY OF SAMPLES FROM CORE WA20 OF THE WAITE AMULET TAILINGS

by

W. Petruk and R.G. Pinard

ABSTRACT

A study was conducted on a suite of samples from different horizons of the Waite Amulet tailings pile to determine the mineralogical characteristics and mineral alterations that have occurred since the tailings were deposited. Data on mineral quantities show that the tailings contain about 60 wt % pyrite and 14 wt % pyrrhotite at 1 m below the water table; about 25 wt % pyrite and 6 wt % pyrrhotite at the water table; about 5 wt % pyrite and 5 wt % pyrrhotite in the unsaturated zone; both minerals are absent in the near surface zone. These data indicate that alteration of sulphide minerals progresses slowly below the water table, faster in the unsaturated zone, and has been completed near surface. The mineral associations provide evidence for the sequential replacement of pyrrhotite but not of pyrite. In particular, the pyrrhotite is transformed from the grain edges towards grain centres to phases which contain various amounts of iron sulphate and water. These phases are in turn converted to a sulphur-rich "goethite". On the other hand, pyrite appears to have altered directly to "goethite".

ÉTUDE MINÉRALOGIQUE ET ANALYSE D'IMAGE DES ÉCHANTILLONS PROVENANT DU CAROTTAGE WA20 DES RÉSIDUS DE WAITE AMULET

par

W. Petruck et R.G. Pinard

RÉSUMÉ

On a fait l'étude d'une gamme d'échantillons recueillis à différents horizons de l'amas de résidus de Waite Amulet en vue de déterminer les caractéristiques minéralogiques et les altérations minérales qui se sont produites depuis que les résidus ont été déposés. Les données relatives aux quantités minérales indiquent que les résidus qui se trouvent à 1 m sous la nappe phréatique ont une teneur en pyrite d'environ 60 % (en poids) et 14 % (en poids) en pyrrhotine; une teneur en pyrite d'environ 25 % (en poids) et 6 % (en poids) en pyrrhotine au niveau de la nappe phréatique; une teneur en pyrite d'environ 5 % (en poids) et 5% (en poids) en pyrrhotine dans la zone non saturée; et que les deux minéraux sont absents près de la surface du sol. Ces données indiquent que l'altération des minéraux sulfurés progresse lentement dans les couches situées sous la nappe phréatique, plus rapidement dans la zone non saturée et qu'elle est totale dans les zones près de la surface. Les minéraux associés font la preuve du remplacement séquentiel de la pyrrhotine mais non de la pyrite. La pyrrhotine, en particulier, est transformée en phases FeS_2 à partir des points intergranulaires vers le centre granulaire. Ces phases sont, à leur tour, changées en "goethite" à haute teneur en soufre. D'autre part, la pyrite semble s'être altérée directement en "goéthite".

INTRODUCTION

A hydrogeochemical investigation is being conducted on the Waite Amulet tailings by Noranda Research Centre and CANMET as part of the Joint Industry/CANMET Reactive Acid Tailings Program. The Waite Amulet tailings area is situated about 20 kilometres north of Noranda, Quebec and contains about 6.5 million tonnes of reactive sulphide tailings. The tailings were deposited prior to 1962 and were successfully vegetated in 1978 and 1979. Lush vegetation covers the tailings pile, but acid seepages are found at the base. The acid is collected in an acid water resevoir and treated in a treatment plant. The objective of the investigation is to determine the biohydrogeochemical processes and controlling mechanisms, in order to develop a long term tailings management program which would eliminate the need for perpetual maintenance and water treatment at the Waite Amulet tailings site, and to develop a model that may be applicable to other tailings.

The study was begun by Noranda Research Centre in September, 1985. They reported that twenty-three piezometer nests were placed, nine cores were taken, the level of the water table was established, pH readings were taken, and bacterial counts were determined for two of the nine cores. They also reported that the pH increases with depth from about 3 to 6 in the unsaturated zone, and is generally greater than 6 below the water table. In addition a strong presence of the sulphur reducing bacteria, thiobacillus ferroxidans, is indicated in the upper 2 metres of the tailings, but the bacteria were not detected below the water table.

A suite of samples from core WA20 (Fig. 1 and 2), taken at 0.3 metre intervals from 0.3 to 3.0 metres below surface, was studied in the Process Mineralogy Section at CANMET to characterize the material. The samples received consisted of unconsolidated material. They were, therefore, screened into plus and minus 37 µm (400 mesh) fractions so that the large grains could be analysed at low power magnification (Table 1). Polished sections were prepared from the screened fractions and studied with the automated MP-SEM-IPS image analysis system. The minerals and phases present were identified with the energy dispersive X-ray analyser (EDXA), the compositions of the alteration products were determined by quantitative analysis with the EDXA, and mineral quantities and the relationships

between the minerals and alteration products were determined with the image analyser.

GENERAL MINERALOGY

The minerals and phases found in the samples are silicates, sulphides, oxides, sulphates and carbonates. The main silicate minerals are quartz, orthoclase, amphibole and/or pyroxene, and chlorite; a minor one is mica. The main sulphide minerals are pyrite and pyrrhotite; minor ones are sphalerite and chalcopyrite; and those in trace amounts are bismuthinite and tetrahedrite. The main oxides are magnetite and goethite, and a minor one is cassiterite. One grain of calcite was found. The sulphates are alteration products of pyrrhotite and pyrite. The main ones are interpreted as $FeSO_4$ with various amounts of FeS_2 and water. In addition a small amount of jarosite was found in samples taken at 0.3 and 1.8 metres. Backscattered electron photographs of the +37 μm (plus 400 mesh) fractions are shown in Fig. 3 to give a pictorial presentation of the mineral distributions in the samples.

ALTERATION PRODUCTS

Pyrrhotite has altered through several stages to a sulphur-rich "goethite", whereas pyrite alters directly to goethite. Alteration of pyrrhotite is evident in all samples taken from 0.6 to 3.0 m but is most pronounced in samples from 1.2 to 2.1 m. The alteration appears as a narrow band around pyrrhotite grains in the sample from 3.0 m, and as wider bands as well as separate particles in samples from closer to surface. By contrast the alteration of pyrite is not apparent in most samples. Data on mineral quantities indicate, however, that pyrite decomposes. Pyrite accounts for about 60 wt % of the material in the sample from 3.0 m, for about 1 to 6 wt % of the material in samples from 0.6 to 1.8 m, and is essentially absent in the sample from 0.3 m.

Pyrrhotite Alteration

At least four types of alteration products were observed on the pyrrhotite particles. The first type (Phase 1) is a phase whose optical properties are similar to those of marcasite, and whose composition is equivalent to FeS_2 (Table 2). This phase surrounds pyrrhotite grains as a band up to 15 micrometres wide (Fig. 4). The second type (Phase 2) also occurs as a band around pyrrhotite grains (Fig. 5). It contains only about 44 wt % Fe and 47 wt % S for a total of 91 wt %, the remainder is assumed to be either oxygen or water since no other elements were indicated by the energy dispersive X-ray (EDXA) spectrum. This composition is equivalent to $7FeS_2 \cdot FeSO_4 \cdot H_2O$; there may be other ways of expressing the composition of this phase. Both phase 1 and 2 contain lamellae (Fig. 6) that probably developed by replacement, along cleavage planes, of pyrrhotite with a hydrous form of $FeSO_4$. Semiquantitative analysis of the lamellae gives a lower total element content than the total for phase 2. Phase 3 has the same texture as phase 2 but the average Fe and S contents are 42 and 44 wt % respectively, for a total of 86 wt % which may be expressed as $2FeS_2 \cdot FeSO_4 \cdot H_2O$. Phase 4 also occurs as bands around pyrrhotite, but it tends to be more massive than phases 1, 2 and 3 (Fig. 7) and contains considerably less sulphur and has a lower Fe plus S total. It contains, in wt %, about Fe 43, S 29, total 72. This composition may be expressed as $FeS_2 \cdot FeSO_4 \cdot H_2O$. The lamellar structure in phases 1, 2 and 3 is retained in some grains that have nearly replaced the pyrrhotite (Fig. 8 and 9) and have compositions that range from the equivalent of $FeS_2 \cdot FeSO_4 \cdot H_2O$ to $FeS_2 \cdot FeSO_4 \cdot 7H_2O$. The apparent end phase of this alteration process is a sulphur-rich "goethite" that contains an average of 38 wt % Fe, 12 wt % S, 1.6 wt % Al and 0.9 wt % Si, for a total of 52 wt % (Table 2) which may be expressed as $FeO \cdot FeSO_4 \cdot 4H_2O$.

Pyrite Alteration

Alteration of pyrite is not readily observed in the samples. However, the quantity of pyrite decreases from about 60 wt % in the sample at 3.0 m to 0.3 wt % in the sample at 0.3 m, which indicates that the alteration products from pyrite have been washed away. The only evidence of pyrite alteration was pyrite remnants in a goethite matrix (Fig. 10). The goethite with pyrite remnants contains 1 to 5 wt % sulphur and small amounts of silicon and aluminium (Table 2).

"Goethite"

The goethite contains less iron than stoichemetric goethite; therefore it is referred to as "goethite". The sulphur-rich "goethite" grains that apparently formed by alteration of pyrrhotite cannot be readily differentiated from the low-sulphur "goethite" grains which probably formed by alteration of pyrite. Therefore, for determination of mineral quantities, both varieties are combined and referred to as "goethite". Both the low- and high-sulphur "goethite" are deposited as borders on all the minerals (Fig. 11, 12 and 13), but the sulphur-rich variety appears to have reacted with magnetite (Fig. 12). Much of the "goethite" in the sample from the near surface zone (Sample 0.3 m) is present as discrete grains (Fig. 14).

Alteration of Chalcopyrite

A trace amount of chalcopyrite is present in all samples but no secondary copper minerals such as covellite or chalcocite were observed.

MINERAL QUANTITIES

Mineral quantities were determined with the image analysis system for both the plus and minus 37 µm (400 mesh) fractions of each sample (Tables 3 and 4). Both sets of data show the same changes from sample to sample. In particular, the pyrite and pyrrhotite contents decrease towards the surface of the tailings pile, but there is no apparent increase in quantity of "goethite" as the quantities of pyrite and pyrrhotite decrease except for the sample from 0.3 m, which contains a high amount of "goethite".

Two types of ternary diagrams were drawn for mineral quantities in the plus and minus 37 µm (400 mesh) fractions to show progressive changes in samples from the base to the surface of the tailings pile. One diagram is a silicate-magnetite-pyrite+pyrrhotite ternary, and the other a pyrite-pyrrhotite-"goethite"+alteration products ternary. The diagrams for both the plus and minus 37 µm (400 mesh) fractions show the same trends (Fig. 15,16,17 and 18). The silicates-magnetite-pyrite+pyrrhotite ternaries show a decrease of pyrite+pyrrhotite towards the magnetite- silicates tie-line, and three zones can be defined by either a grouping of points or a progressive change in point positions. The zones are:

(1) below 2 m (below the water table), (2) 0.6 to 2 m (unsaturated zone), and (3) above 0.6 m (near surface). It is noteworthy that for samples from below the water table the mineralogical proportions of Sample 2.1 m (No. 7) fall between that of Sample 2.7 m (No. 9) and 3.0 m (No. 10). By contrast, the mineralogical composition indicates that Sample 2.4 m (No. 8) is more altered than any other sample from below the water table.

The mineralogical proportions of the samples from the unsaturated zones are significantly different than for samples from below the water table and from the near surface zone. Pyrite plus pyrrhotite account for about 80 wt % of the material in the sample at 3.0 m, for about 5 to 25 wt % in the unsaturated zone, and for less than 0.5 wt % near surface.

The pyrite-pyrrhotite-"goethtite+altered products ternary diagrams show the same trends for plus and for the minus 37 μm (400 mesh) fractions, but there is a better grouping for the plus 37 μm (400 mesh) fraction samples. It is noteworthy that Sample 3.0 m (No. 10) contains some goethite, and the pyrrhotite in the sample in partly altered. Furthermore, the position of the point for Sample 2.1 (No. 7) is between the position of the points for Samples 2.7 (No. 9) and 3.0 (No. 10), and the position of the point for Sample 2.4 (No. 8) is close to the water table boundary. This sequence for the samples from below the water table is the same as in the silicates-magnetite-pyrite+pyrrhotite ternary diagram. The points on the pyrite-pyrrhotite-"goethite"+altered products ternary diagram suggest that, below the water table, pyrrhotite alters at a faster rate than pyrite. Another observation is that the pyrite-pyrrhotite-goethite+ alteration products ternary shows a grouping of Samples 0.6 m to 1.8 m (No. 2-6) for the unsaturated zone rather than 0.9 to 1.8 (No. 3-6) as in the silicates-magnetite-pyrite+pyrrhotite ternary. This suggests that sample 0.6 is at the boundary between the saturated zone and a near surface zone. Sample 0.3 m which is from near surface, has a high "goethite" content and essentially no pyrite or pyrrhotite.

DISCUSSION

The mineralogical investigation has shown that (1) there is a progressive change in mineral quantities from the base to the surface of the tailings pile; (2) the tailings below the water table, in the unsaturated zone, and in the near surface zone have distinct mineralogical characteristics; and (3) alteration proceeds by transformation from pyrrhotite to an iron sulphate which in turn breaks down to a sulphur-rich "goethite", and by break down of pyrite to a low-sulphur "goethite". The amount of "goethite" in the tailings pile is relatively low which suggests that much of the iron and sulphur that were produced from the pyrite and pyrrhotite were probably washed away. It is possible, however, that some of the leached iron has remained and has been converted to magnetite.

The results given in Tables 3 and 4 indicate that (a) pyrite and pyrrhotite are essentially absent in the near surface zone; (b) about 10 to 30 per cent of the amount of pyrite and pyrrhotite assumed to have been present in the original tailings is still present in the unsaturated zone; and (c) about 1/2 the amount of pyrite and 1/4 the amount of pyrrhotite are still present just below the water table. It was also observed that the alteration bands on pyrrhotite are much wider in Samples 2.4 and 2.7 (2.4 to 2.7 m below the water table) than in Sample 3.0 (3.0 metres below the water table). These results suggest that decomposition of pyrite and pyrrhotite has been completed in the near surface zone, is progressing at a relatively high rate in the unsaturated zone, and at a slow rate below the water table. It is possible, however, that there is no decomposition of pyrite and pyrrhotite below the water table, but that, during the period from 1962 to 1985 the water table fluctuated between 2 and 3 metres below the surface of the tailings pile giving rise to the observed changes in mineralogical compositions below the present water table.

TABLE 1. Wt % of samples in sized fractions

Sample depth (m)	>37 µm fractions	<37 µm fractions	TOTAL
.30	93.98	6.62	100.00
.60	92.77	7.23	100.00
.90	92.10	7.90	100.00
1.20	96.52	3.48	100.00
1.50	94.33	5.67	100.00
1.80	94.05	5.95	100.00
2.10	93.26	6.74	100.00
2.40	94.47	5.53	100.00
2.70	85.08	14.92	100.00
3.00	92.14	7.86	100.00

TABLE 2. Quantitative EDXA analysis for minerals

Mineral	Sample	Fraction	Elements in wt %						Total
			Fe	S	K	Ca	Al	Si	
Pyrite	0.9m	>37 µm	47.0	54.3					101.3
Pyrite	1.2m	>37 µm	47.6	54.1					101.7
Pyrite	1.5m	>37 µm	47.7	53.5					101.2
Pyrite	1.8m	>37 µm	46.5	53.2					99.7
Pyrite	2.1m	>37 µm	47.0	54.3					101.3
Pyrite	2.1m	>37 µm	47.9	53.6					101.5
Pyrite	2.1m	>37 µm	45.6	53.1					98.7
Pyrite	2.4m	>37 µm	48.3	54.1					102.4
Pyrite	2.4m	>37 µm	47.0	53.5					100.5
Pyrite	2.7m	>37 µm	48.6	54.9					103.5
Pyrite	3.0m	>37 µm	47.9	55.0					102.9
Pyrite	3.0	<37 µm	47.3	54.8					102.1
Pyrrh.	0.9m	>37 µm	62.7	39.4					102.1
Pyrrh.	1.2m	>37 µm	61.6	39.4					101.1
Pyrrh.	1.2m	>37 µm	62.0	38.9					100.9
Pyrrh.	1.5m	>37 µm	62.2	37.8					100.0
Pyrrh.	2.4m	>37 µm	62.8	38.1					100.9
Pyrrh.	2.4m	>37 µm	59.8	38.5					98.3
Pyrrh.	2.7m	<37 µm	59.8	39.0					98.8
Pyrrh.	2.7m	<37 µm	57.9	40.9					98.8
Pyrrh.	3.0m	<37 µm	61.0	39.3					100.3
AP-type1	1.5m	>37 µm	42.6	54.1	-	0.2	-	0.1	97.1
AP-type2	1.5m	>37 µm	48.2	43.8	-	-	-	-	92.0
AP-type2	2.1m	>37 µm	42.7	50.2	-	-	-	-	92.9
AP-type2	2.7m	<37 µm	46.4	45.6	-	-	-	-	93.0
AP-type2	2.7m	<37 µm	41.8	48.4	-	-	-	-	90.2
AP-type2	2.7m	<37 µm	43.5	48.6	-	-	-	-	92.1
AP-type2	2.7m	<37 µm	43.0	48.0	-	-	-	-	91.0
AP-type2	ave.		44.3	47.4	-	-	-	-	91.7
AP-type3	1.8m	>37 µm	45.8	40.6	-	-	-	-	86.4
AP-type3	1.8m	>37 µm	42.8	42.4	-	-	-	0.3	85.5
AP-type3	2.7m	<37 µm	40.3	45.9	-	-	-	-	86.2
AP-type3	2.7m	<37 µm	40.0	46.0	-	-	-	-	86.0
AP-type3	ave.		42.2	43.7	-	-	-	0.1	86.0
AP-type4	1.5m	>37 µm	44.9	27.5	-	-	-		72.4
AP-type4	1.8m	>37 µm	41.6	37.8	-	-	0.3	0.2	79.9
AP-type4	2.1m	>37 µm	44.5	25.9	0.1	-	0.3	0.4	71.2
AP-type4	2.4m	>37 µm	44.5	27.0	-	-	0.1	0.2	71.8
AP-type4	2.4m	>37 µm	47.3	25.9	-	-	1.0	0.3	75.5
AP-type4	2.7m	>37 µm	44.1	34.4	-	0.2	0.1	0.2	79.0
AP-type4	2.7m	<37 µm	37.9	40.9	-	-	-	-	78.8
AP-type4	2.7m	<37 µm	42.4	16.7	-	-	-	-	60.1

AP = alteration product

AP-type4	2.7m	<37 µm	39.1	29.3	-	-	0.5	0.3	69.2
AP-type4	2.7m	<37 µm	42.3	16.6	-	-	-	-	58.9
AP-type4	2.7m	<37 µm	42.0	28.2	-	-	1.7	0.1	72.0
AP-type4	2.7m	<37 µm	40.2	32.3	-	-	-	-	72.5
AP-type4	ave.	<37 µm	42.6	28.6	-	-	0.3	0.1	71.6
AP-type?	2.4m	<37 µm	29.0	24.7	-	-	-	0.2	53.9
Goethite	0.6m	>37 µm	35.1	8.9	0.2	-	1.4	2.0	47.6
Goethite	0.9m	>37 µm	41.0	8.2	-	-	2.7	0.5	52.4
Goethite	0.9m	>37 µm	38.8	9.5	-	-	3.0	0.5	51.8
Goethite	0.9m	>37 µm	34.1	9.6	-	-	2.5	0.6	46.8
Goethite	0.9m	>37 µm	32.8	12.5	-	-	3.6	1.1	50.0
Goethite	1.2m	>37 µm	30.8	8.6	-	-	2.9	4.4	46.7
Goethite	1.2m	>37 µm	38.6	9.0	0.1	0.3	2.2	-	50.2
Goethite	1.2m	>37 µm	44.1	9.9	-	-	1.9	0.7	56.6
Goethite	2.1m	>37 µm	47.7	11.3	0.1	-	0.3	0.7	60.1
Goethite	2.4m	>37 µm	43.5	13.7	-	-	1.5	0.8	59.5
Goethite	2.7m	>37 µm	35.7	19.8	-	0.2	-	0.3	56.0
Goethite	3.0m	>37 µm	24.4	17.9	-	-	-	0.3	42.6
Goethite	2.7m	<37 µm	32.9	17.2	-	-	-	0.4	50.5
Goethite	2.4m	<37 µm	52.5	9.6	0.1	-	0.3	0.5	63.0
Goethite	ave.		38.0	11.8	-	-	1.6	0.9	52.3
Goethite	0.3m	>37 µm	52.8	2.4	-	-	-	0.5	55.7
Goethite	0.3m	>37 µm	54.3	2.0	0.2	-	0.2	0.6	57.3
Goethite	0.3m	>37 µm	50.2	5.1	0.7	-	0.3	0.9	57.1
Goethite	0.3m	>37 µm	52.6	2.5	-	-	-	0.5	55.6
Goethite	0.3m	>37 µm	48.6	5.1	0.8	-	0.5	0.8	55.8
Goethite	0.3m	>37 µm	45.3	1.1	-	-	-	5.4	51.8
Goethite	0.6m	>37 µm	50.3	1.6	0.1	-	0.4	3.2	55.6
Goethite	0.6m	>37 µm	53.8	2.6	0.1	-	0.5	0.5	57.5
Goethite	0.6m	>37 µm	46.0	2.8	-	-	0.2	0.9	49.9
Goethite	0.9m	>37 µm	49.8	4.6	-	-	1.2	0.6	56.2
Goethite	1.2m	>37 µm	42.4	5.2	-	-	3.3	0.3	51.2
Goethite	1.5m	>37 µm	48.8	5.0	-	-	2.4	0.5	56.7
Goethite	1.5m	>37 µm	47.6	2.1	0.1	-	0.5	2.0	52.3
Goethite	1.8m	>37 µm	49.0	3.3	0.1	-	0.1	0.3	52.8
Goethite	1.8m	>37 µm	41.6	4.7	0.1	-	0.5	0.5	47.4
Goethite	2.1m	>37 µm	53.1	4.5	-	-	0.2	0.8	58.6
Goethite	2.4m	>37 µm	46.5	2.0	0.1	0.3	1.5	4.1	54.5
Goethite	2.7m	>37 µm	48.5	1.7	-	0.2	0.6	2.5	53.5
Goethite	2.4m	<37 µm	50.2	4.9	-	0.3	1.2	0.6	57.2
Goethite	2.4m	<37 µm	46.7	1.8	-	-	1.2	0.8	50.5
Goethite	ave.		48.8	3.3	0.1	-	0.7	1.3	54.2
Jarosite	0.3m	>37 µm	26.6	10.5	3.8	-	-	0.6	41.5
Jarosite	1.8m	>37 µm	36.3	3.6	2.1	-	-	0.6	42.6

TABLE 3. Mineral quantities in >37 μm (+400 mesh) fractions

Mineral	Depth of Samples (metres)									
	0.3 wt %	0.6 wt %	0.9 wt %	1.2 wt %	1.5 wt %	1.8 wt %	2.1 wt %	2.4 wt %	2.7 wt %	3.0 wt %
Quartz	27.4	37.5	56.5	41.4	12.6	34.3	14.4	19.3	26.1	7.2
Orthoclase	6.9	10.3	9.2	11.0	4.9	14.9	2.5	8.5	6.4	2.0
Chlorite	1.7	1.6	4.3	7.0	2.7	7.4	2.3	6.2	3.9	1.3
Amph.+pyrox.	2.5	1.8	6.4	7.1	1.8	7.0	2.3	6.1	3.3	0.8
Goethite	14.2	1.4	5.1	8.1	5.8	7.3	2.8	6.3	3.1	1.1
Pyrite	0.3	2.1	5.4	2.9	3.5	5.9	45.5	25.5	21.4	62.5
Magnetite/ hematite	46.8	43.6	10.4	13.5	37.9	7.5	12.7	19.4	18.6	7.5
Altered pyrr.	0.0	0.1	0.4	2.0	12.2	7.3	5.8	5.1	2.9	2.4
Pyrrhotite	0.0	0.1	1.1	5.9	17.2	6.5	10.8	3.0	13.7	14.1
Chalcopy+sph.	0.0	1.3	1.0	1.1	0.5	1.9	0.7	0.5	0.6	1.1
Arsenopy+tet.	-	-	-	-	0.1	-	-	-	-	-
Gal.+cass.	0.1	0.2	0.2	0.0	0.7	0.0	0.2	0.1	0.1	0.0
Goeth. on sil.	0.7	0.5	0.8	1.0	0.5	1.0	0.3	1.1	0.5	0.2
Goeth. on mag.	1.1	0.2	0.1	0.6	0.8	0.6	0.2	0.5	0.2	0.1
Goeth. on pyr.	0.0	0.0	0.1	0.2	0.4	0.9	0.5	0.5	0.3	0.1

TABLE 4. Mineral quantities in <37 μm (-400 mesh) fractions

Mineral	Depth of Samples (metres)									
	0.3 wt %	0.6 wt %	0.9 wt %	1.2 wt %	1.5 wt %	1.8 wt %	2.1 wt %	2.4 wt %	2.7 wt %	3.0 wt %
Quartz	19.6	19.3	32.4	12.5	18.2	12.4	14.0	12.1	22.0	8.3
Orthoclase	10.5	8.7	13.3	5.8	8.9	7.0	4.4	7.2	7.0	3.6
Chlorite	1.7	1.8	5.7	3.8	2.9	2.4	3.4	2.7	3.2	2.1
Amph.+pyrox.	3.1	7.5	12.9	15.4	8.0	11.0	8.7	8.2	8.4	3.8
Goethite	32.2	14.7	12.7	35.6	24.1	38.6	13.8	18.1	10.6	2.8
Pyrite	0.0	4.0	5.1	4.4	5.5	7.0	30.8	20.1	14.4	53.2
Magnetite/ hematite	33.8	41.4	14.2	14.7	21.3	15.4	18.3	20.8	14.3	8.7
Altered pyrr.	0.2	0.1	0.4	2.3	6.6	2.8	6.6	7.7	4.7	3.8
Pyrrhotite	0.2	0.2	1.9	4.3	4.2	1.6	4.2	2.7	14.1	11.6
Chalcopy+sph.	0.0	2.3	0.4	1.1	0.1	1.0	1.4	0.4	1.1	1.2
Arsenopy+tet.	-	-	0.3	-	-	-	-	-	-	0.1
Gal.+cass.	0.7	0.1	0.8	0.1	0.2	0.7	0.4	0.1	0.2	0.8

*magnetite could include hematite; pyrr. = pyrrhotite; sph. = sphalerite; tet. = tetrahedrite; gal. = galena; cass. = cassiterite; goeth. = "goethite"; sil. = silicates; mag. = magnetite; pyr. = pyrite

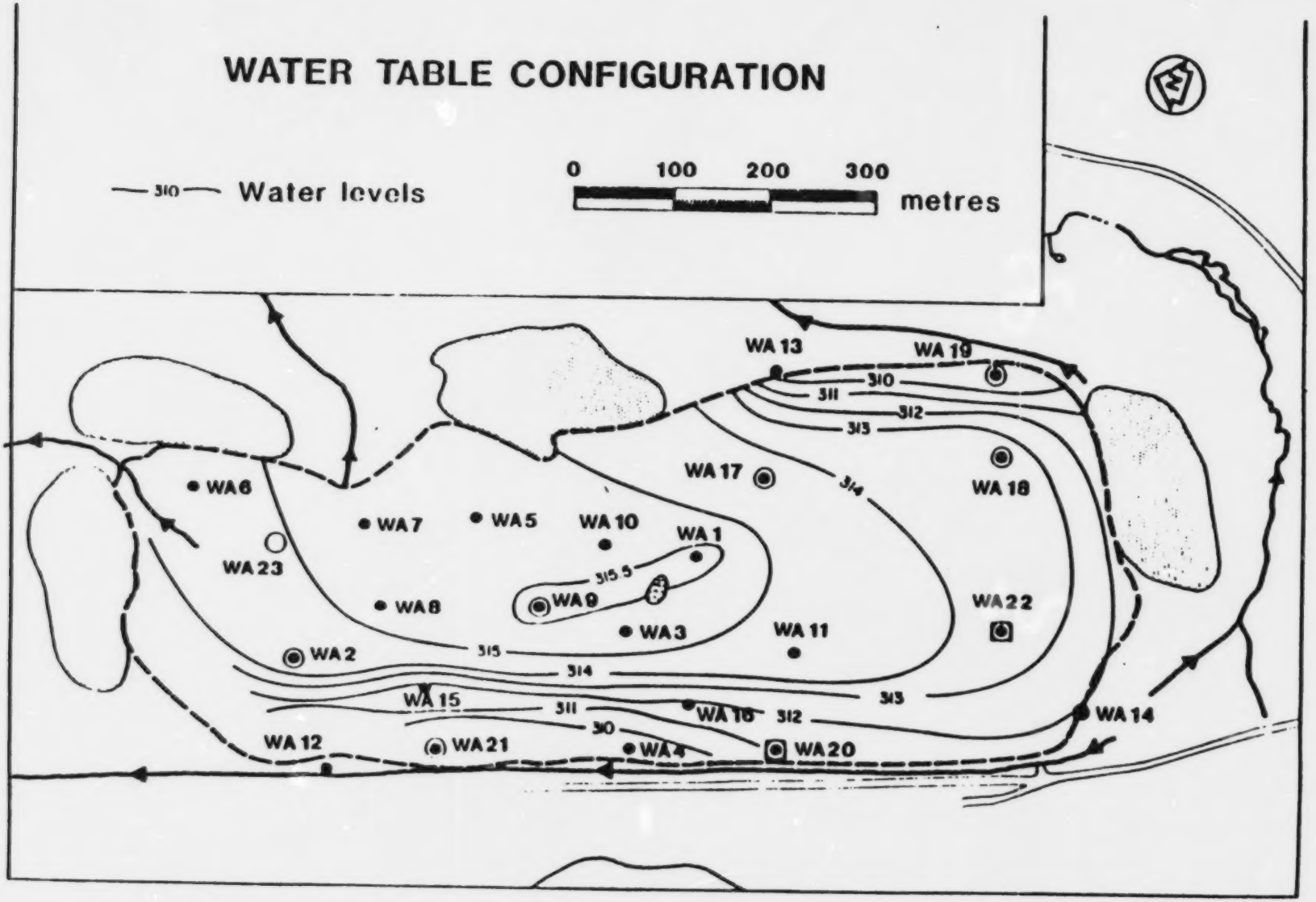


Fig. 1. Plan of Waite Amulet Tailings pile showing locations of piezometer nests, drill core sites, and water table horizons (from report submitted by Noranda Mines)

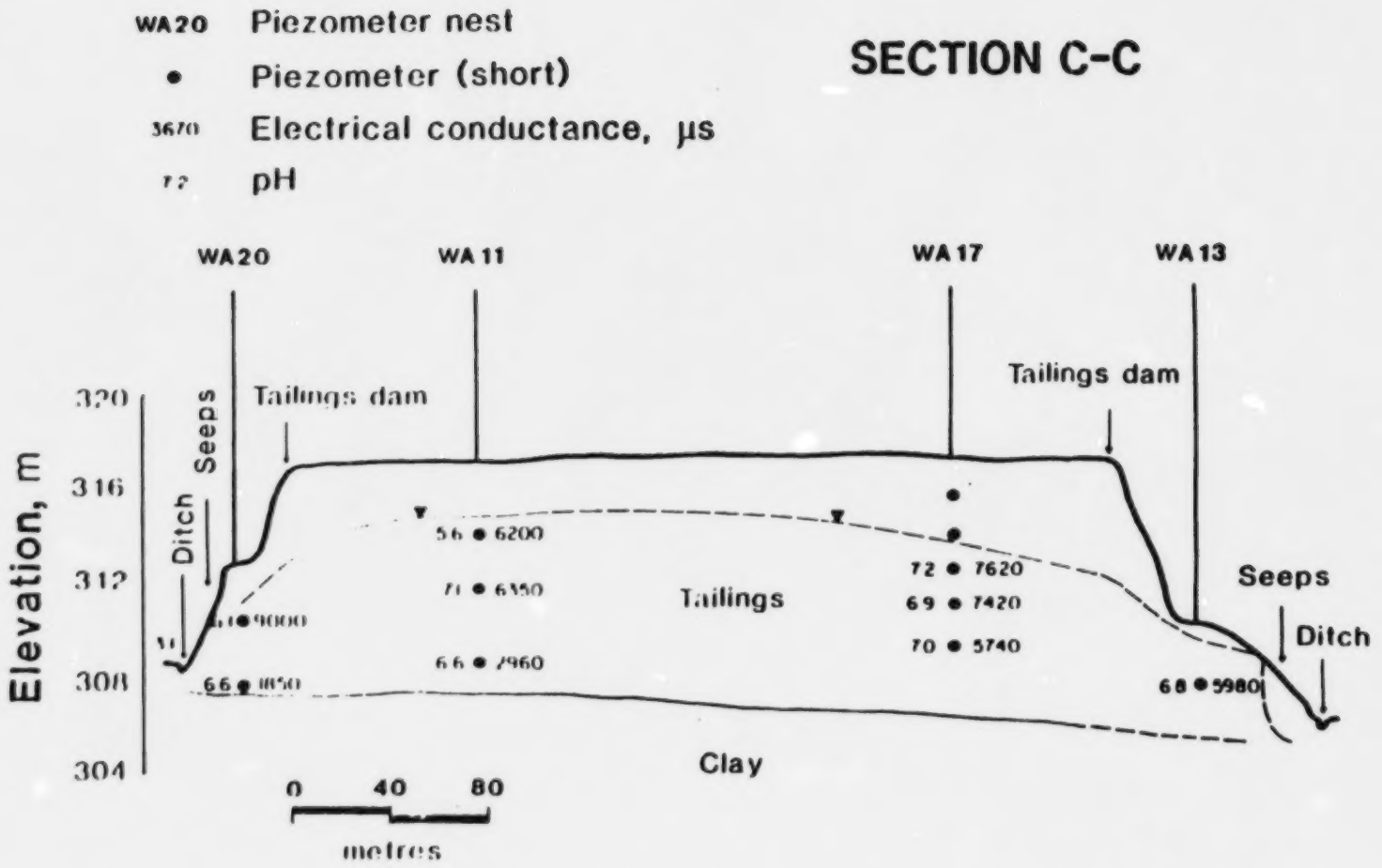


Fig. 2. Cross-section of Waite Amulet tailings pile showing location of drill core WA20 (from report submitted by Noranda Mines)

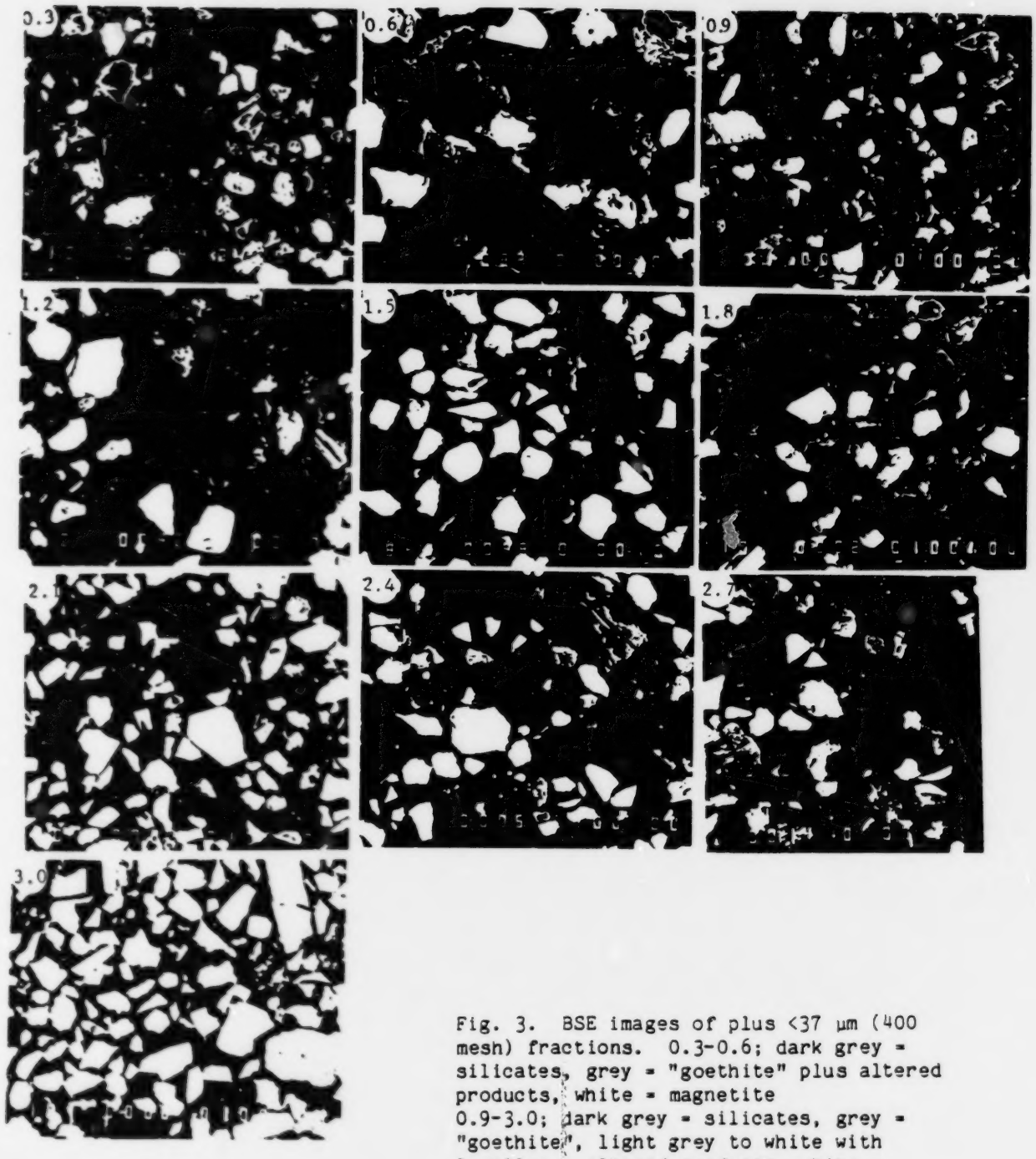


Fig. 3. BSE images of plus <37 μm (400 mesh) fractions. 0.3-0.6; dark grey = silicates, grey = "goethite" plus altered products, white = magnetite
0.9-3.0; dark grey = silicates, grey = "goethite", light grey to white with lamellae = altered products, white = pyrite, pyrrhotite and magnetite

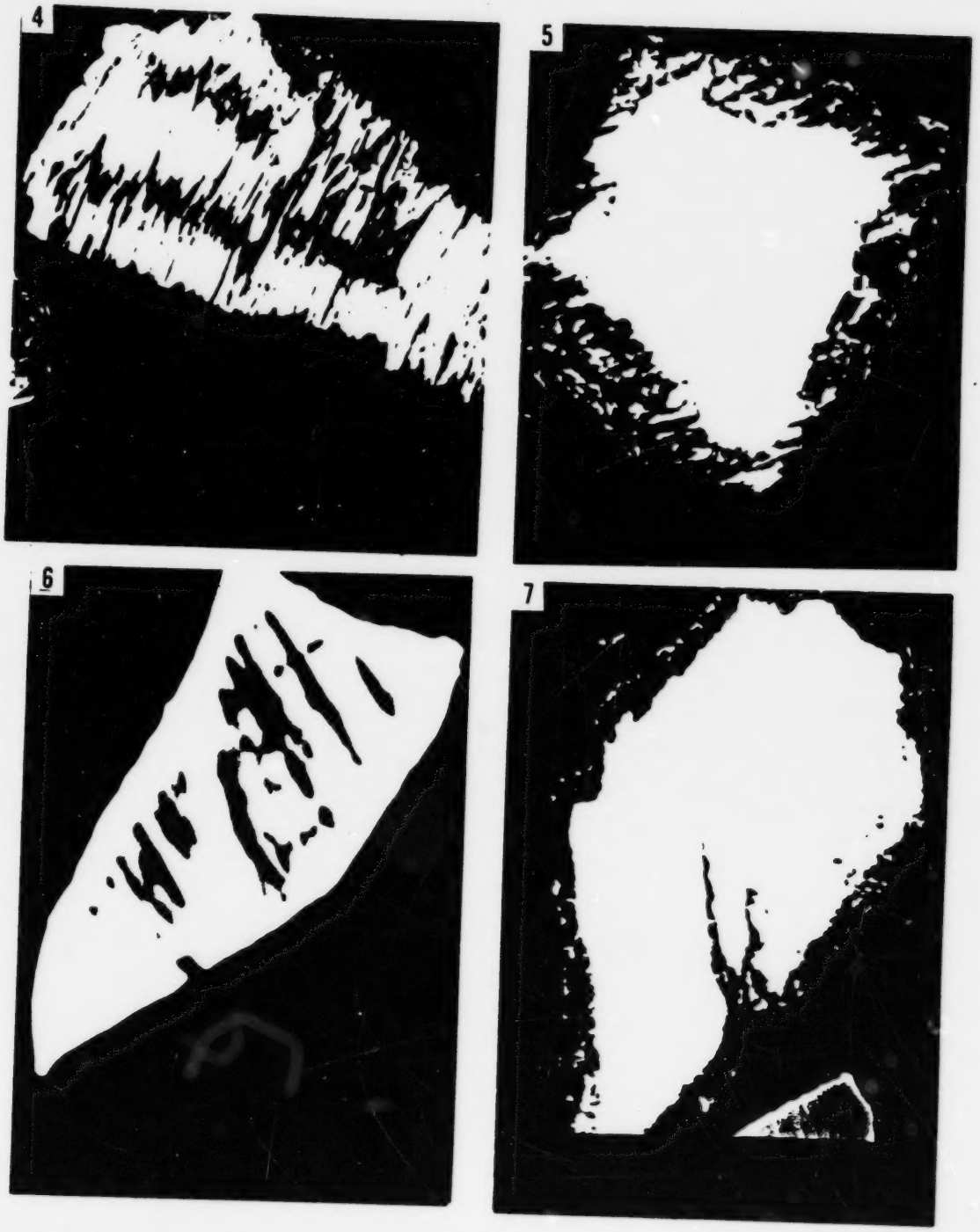
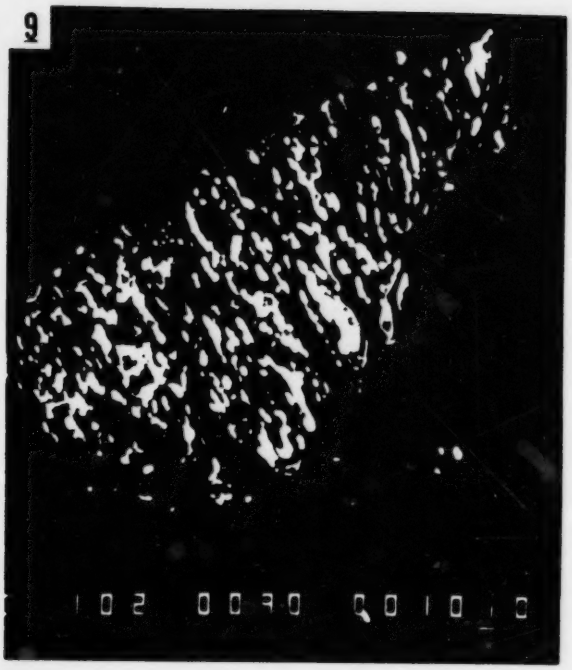


Fig. 4. BSE image showing pyrrhotite (white) surrounded by phase 1 alteration product.

Fig. 5. BSE image showing pyrrhotite (white) surrounded by phase 2 alteration product.

Fig. 6. BSE image of an alteration product (phase 3) showing lamellae that are assumed to be $FeSO_4$.

Fig. 7. BSE image showing pyrrhotite (white) bordered by phase 4 alteration product.



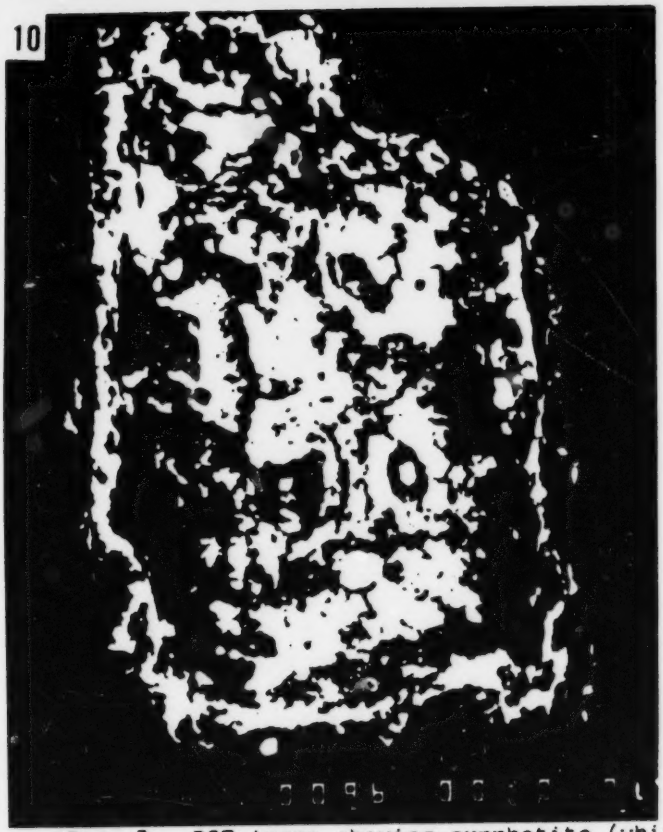


Fig. 8. BSE image showing pyrrhotite (white) partly replaced by alteration products.
Fig. 9 BSE image showing pyrrhotite nearly replaced by an alteration product.
Fig. 10. Pyrite remnants in "goethite".

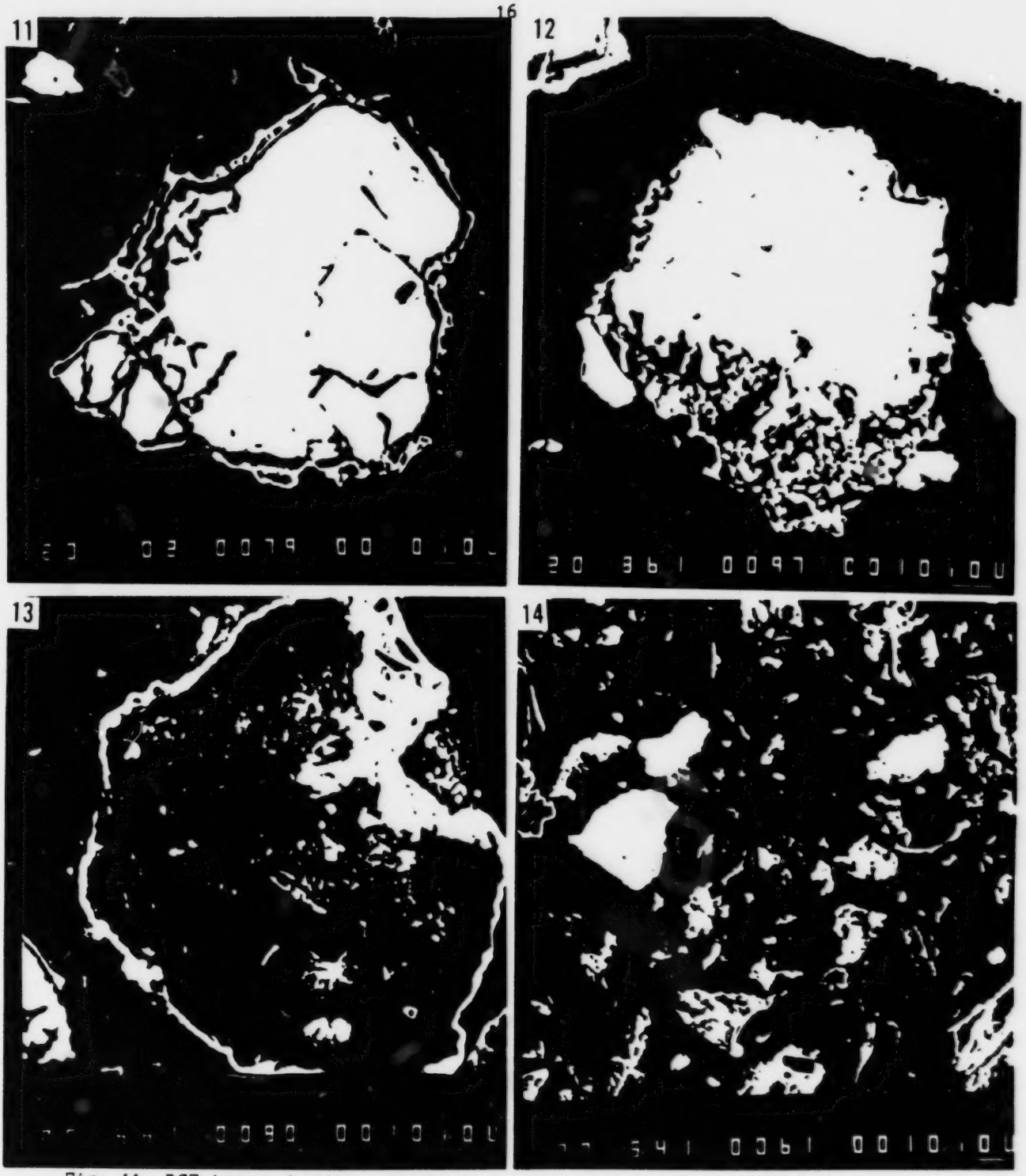


Fig. 11. BSE image showing a magnetite grain bordered by a low-sulphur "goethite".

Fig. 12. BSE image showing a magnetite grain bordered by a sulphur-rich "goethite". The magnetite in the lower part of the diagram appears to have been partly replaced by the "goethite".

Fig. 13. BSE image showing a quartz grain bordered by "goethite".

Fig. 14, BSE image of the sample at 0.3 m (near surface) showing discrete grains of "goethite" (grey) and magnetite (white).

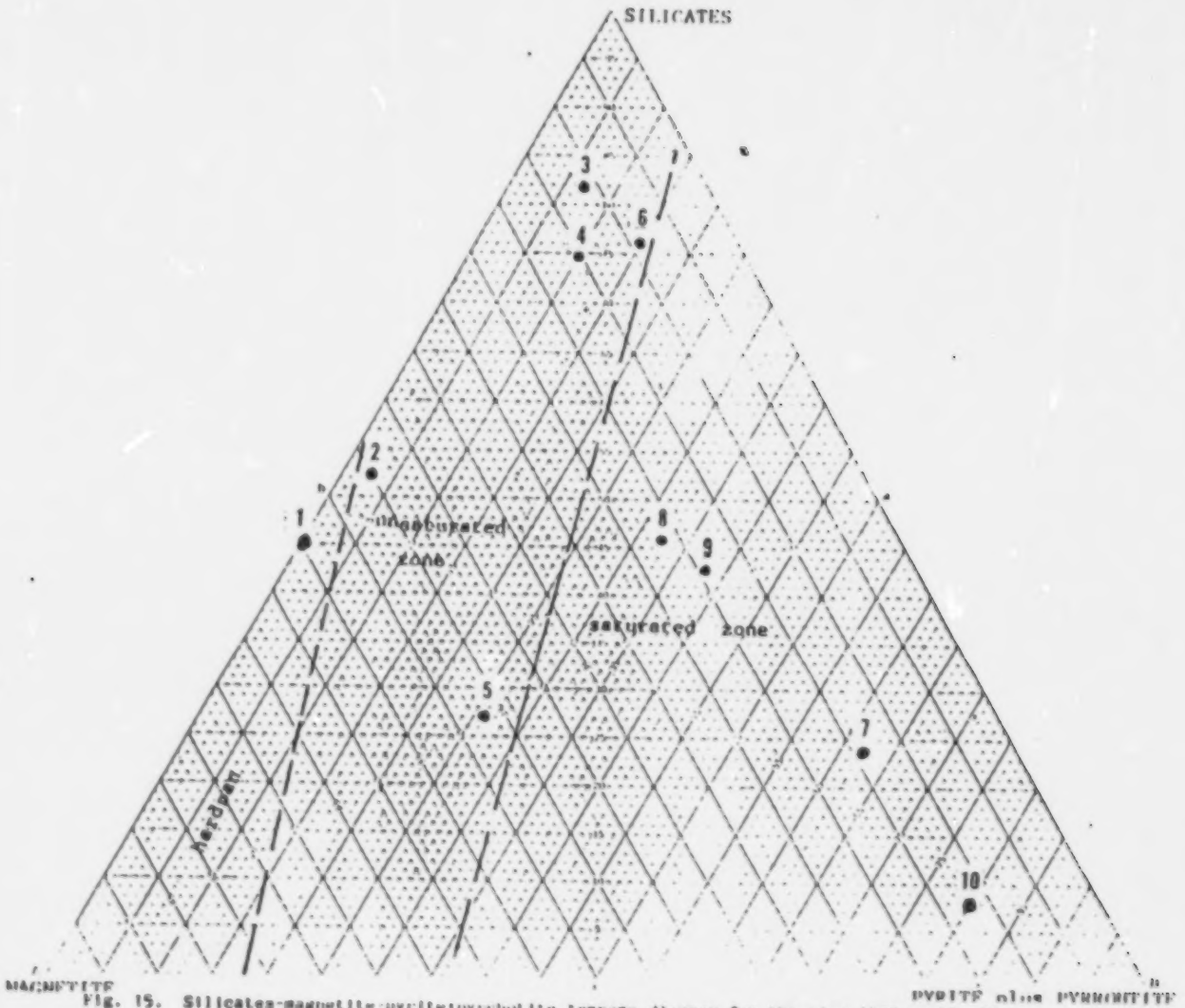


Fig. 15. Silicates-magnetite-pyrite-pyrrhotite ternary diagram for the plus (400 mesh) >37 μm fractions. 1 - 0.3 m, 2 - 0.6 m, 3 - 0.9 m, 4 - 1.2 m, 5 - 1.5 m, 6 - 1.8 m, 7 - 2.1 m, 8 - 2.4 m, 9 - 2.7 m, 10 - 3.0 m.

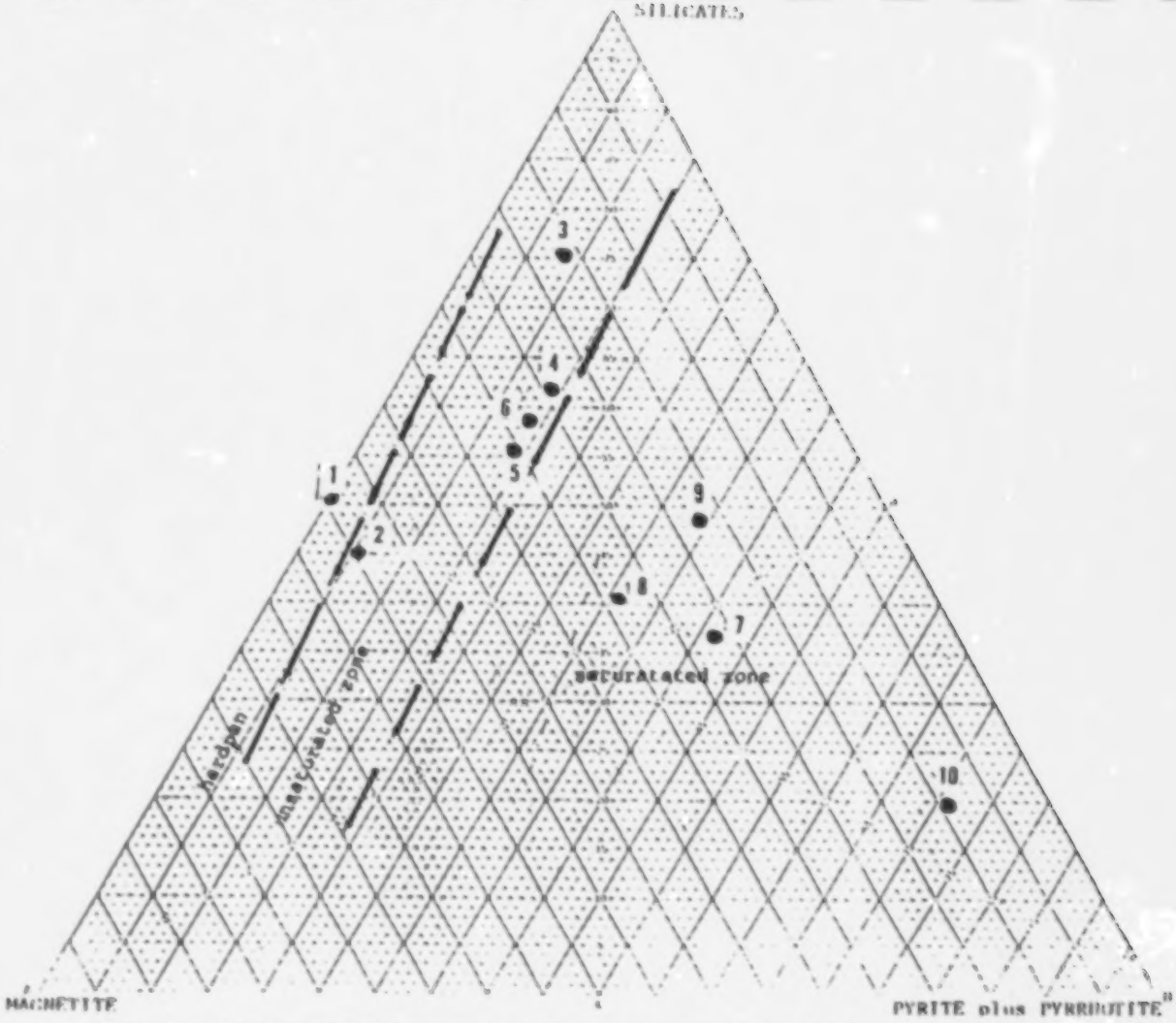


Fig. 16. Silicates-magnetite-pyrite-pyrrhotite ternary diagram for the minus <37 μm (400 mesh) fractions. 1 = 0.3 m, 2 = 0.6 m, 3 = 0.9 m, 4 = 1.2 m, 5 = 1.5 m, 6 = 1.8 m, 7 = 2.1 m, 8 = 2.4 m, 9 = 2.7 m, 10 = 3.0 m.

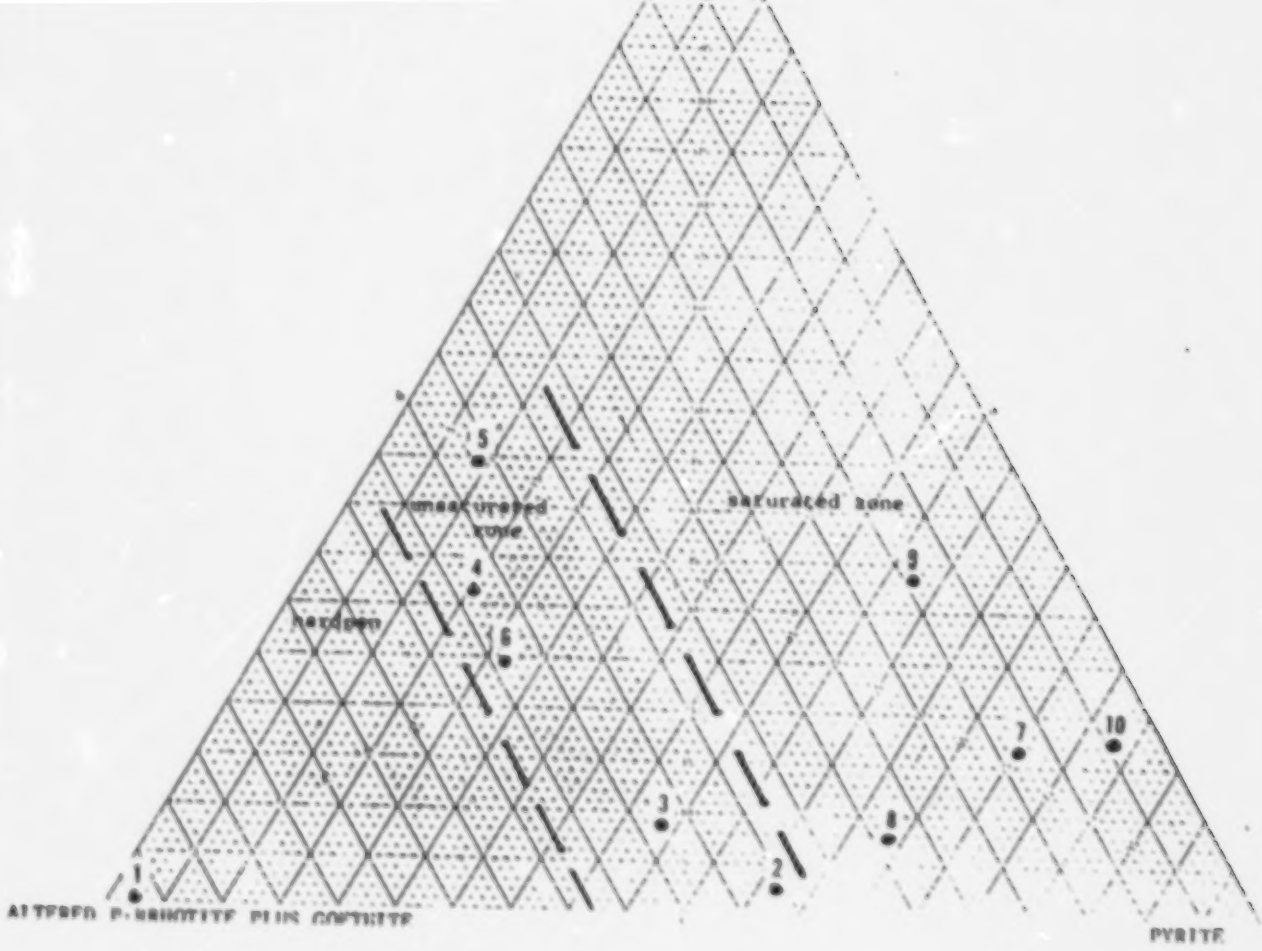


Fig. 17. Pyrite-pyrrhotite-goethite + alteration products ternary diagram for >37 μm (plus 400 mesh) fractions. 1 = 0.3 m, 2 = 0.6 m, 3 = 0.9 m, 4 = 1.2 m, 5 = 1.5 m, 6 = 1.8 m, 7 = 2.1 m, 8 = 2.4 m, 9 = 2.7 m, 10 = 3.0 m.

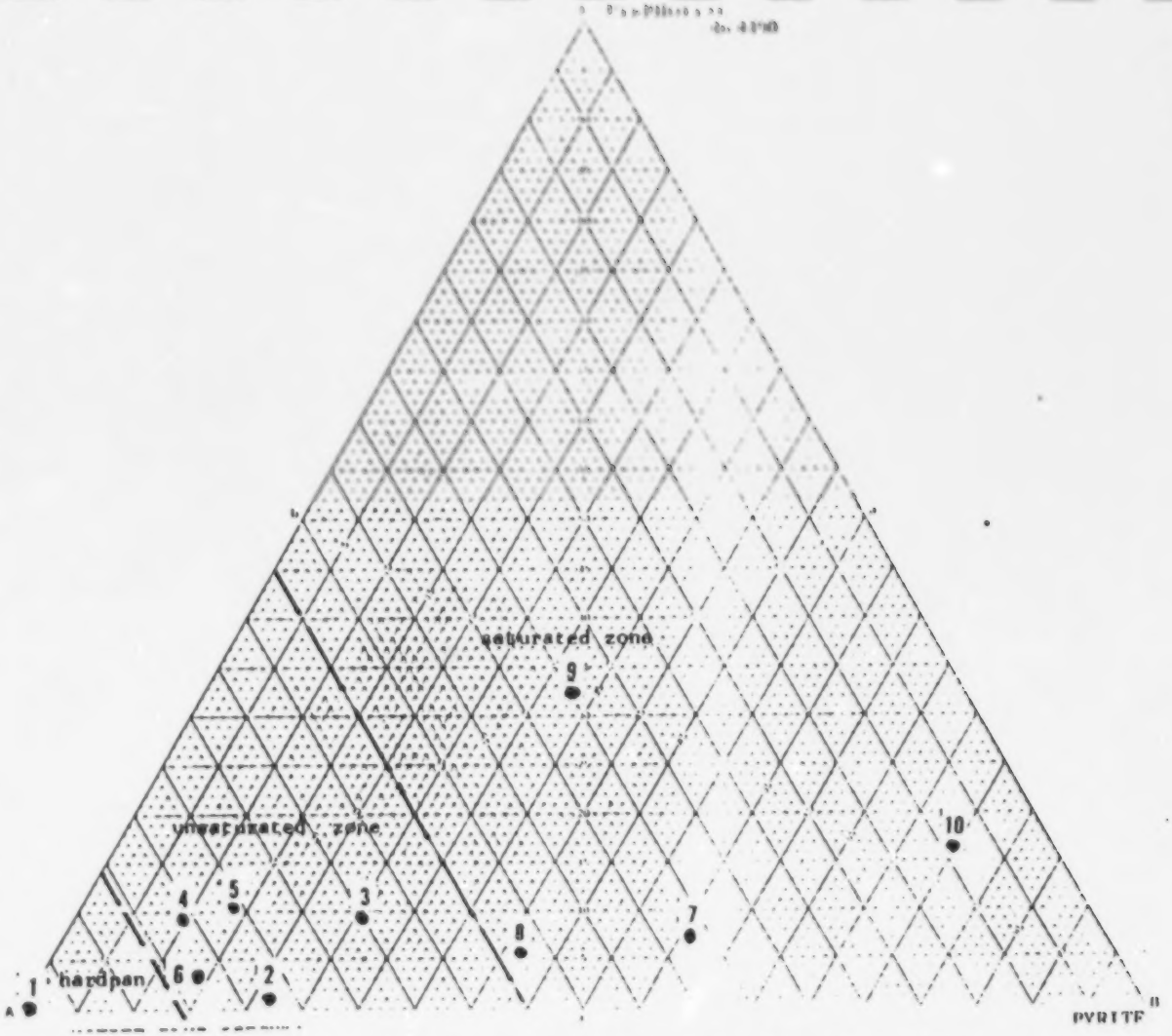


Fig. 18. Pyrite-pyrrhotite-goethite + alteration products ternary diagram for the <37 μm (minus 400 mesh) fractions. 1 = 0.3 m, 2 = 0.6 m, 3 = 0.9 m, 4 = 1.2 m, 5 = 1.5 m, 6 = 1.8 m, 7 = 2.1 m, 8 = 2.4 m, 9 = 2.7 m, 10 = 3.0 m.

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DETAILED MINERALOGICAL EXAMINATION OF ALTERATION PRODUCTS IN CORE WA20 FROM WAITE AMULET TAILINGS

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ABSTRACT

Alteration of the Waite Amulet tailings has resulted in the formation of (1) a strongly oxidized upper zone largely depleted of sulphides; (2) an intermediate zone wherein pyrrhotite, which is the sulphide most susceptible to alteration, has been replaced extensively; (3) a bottom zone in which pyrrhotite is largely intact. Pyrrhotite in the oxidized zone has been replaced mainly by goethite, but in the intermediate zone the alteration products are goethite, native sulphur, marcasite, and iron sulphates that are probably of the type $FeSO_4.nH_2O$. Other alteration minerals are bassanite, gypsum, lepidocrocite, and jarosite.

INTRODUCTION

The Waite Amulet minesite is about 20 km north of Noranda, Quebec. The original mill at the mine was constructed in 1929, and feed from ten separate orebodies in the area was eventually passed through the mill prior to its closure in 1962. Siwik (1986) reports that the operations resulted in 5.9 million tonnes of sulphide-rich tailings, 2 to 15 m thick, that are in an elevated 41 hectare dam. The tailings and site are undergoing detailed hydrogeochemical studies as part of the national RATS (Reactive Tailings Study) program. In this specific case Noranda Research Centre and CANMET are joint participants in the study.

As part of the Waite Amulet investigation, nine holes were cored through the tailings pile in 1985. Core samples from hole WA20 were examined mineralogically by Petruk and Pinard (1985), and their image analysis study provided quantitative abundances of the tailings minerals and alteration products that occur in one vertical section through the tailings pile. The alteration products are complex and extremely fine-grained mixtures that are difficult to identify as specific mineral phases. The main objective of the present study was to investigate in more detail the mineralogical character of the alteration products to see whether they are largely amorphous or crystalline, and to identify the crystalline phases.

SAMPLES AND STUDY METHODS

Ten tailings samples (WA20-1 to WA20-10) were available. These had been screened into +37 micrometre (+400 mesh) and -37 micrometre fractions, and bottled separately. As well, the 20 polished sections used by Petruk and Pinard (1986) in their study of these screened fractions were available.

Only the coarser (+37 micrometre) fractions were used in the present investigation. A cursory examination of the ten polished sections showed that there was considerable mineral variation from sample to sample, as is evident in the image analysis results obtained by Petruk and Pinard (see Table 1). Consequently, a portion of the tailings was removed from each of the 10 bottles of +37 micrometre sample, and each was separated into three fractions according to the reaction to a hand magnet. The fractions were examined megascopically (Table 2) and under a binocular microscope, and aggregated material (clumps) was selected for an additional nine polished sections. Eventually about forty Debbye-Scherrer X-ray patterns were obtained from material selected under the metallographic or binocular microscopes, and a few supplementary energy dispersion and wavelength microprobe analyses were used to confirm the X-ray diffraction and microscopic observations.

RESULTS

Hand-magnet separations

Table 2 summarizes the megascopic observations resulting from the magnetic separation of the +37 micrometre samples. In all samples the colour of the magnetic fraction is darker than that of the non-magnetic fraction because magnetite and pyrrhotite report to the magnetic portion whereas the light-coloured silicates are left behind. As shown in Table 2, both the magnetic and non-magnetic fractions of all samples except WA20-6 show progressive colour darkening with increasing depth. The reversal for WA20-6 probably reflects its relatively high goethite content combined with a low content of magnetite plus total sulphides (Table 1).

The hand-magnet separations resulted in a pronounced size grading in that nearly all of the coarse material was removed from the non-magnetic fraction and reported in variable proportions to both of the magnetic fractions, though predominantly to the more magnetic one. This coarse material consists of weakly to moderately cohesive aggregates that form clumps up to 5 mm in diameter, though most are 2 mm or less. These larger clumps contain the same mineral species that are present in the associated non-aggregated and minutely aggregated fractions, but some clumps show clearly that layering is present (Fig. 1). The layering is evident mainly because of variations in the proportions of minerals such as pyrite, pyrrhotite, and magnetite. Differences in grain sizes are less conspicuous, but a few examples have been observed (Fig. 2,3). These observations, together with the data of Petruk and Pinard (Table 1), fit well with the assumption that substantial changes in mineral proportions occurred during the many years of tailings deposition. Post-depositional, in situ alteration is only of secondary importance in accounting for major mineral variations in all samples except those nearest the surface.

Alteration minerals

Bassanite, $CaSO_4.1/2H_2O$, occurs in small amounts throughout the tailings cross-section. Under a binocular microscope the mineral can be seen as snow-white partial coatings on some grains, and as an interstitial binder among grain aggregates. Gypsum, $CaSO_4.2H_2O$, was identified in only one X-ray diffraction pattern and is present with admixed bassanite. Anhydrite, $CaSO_4.H_2O$, has not been detected.

Bassanite is unstable when exposed to water, and thus is lost readily in the routine preparation of polished sections. Dissolution of bassanite accounts for its absence in the image-analysis sections, and similarly accounts for the excessive pitting observed in some of the clumps mounted in sections.

Jarosite, $KFe_3(SO_4)_2(OH)_6$, occurs mainly in the near-surface oxidized zone. X-ray powder patterns show that the mineral deviates from its end-member composition, but energy dispersion analyses of the X-ray mounts indicate that substantial amounts of potassium are present. The mineral is, therefore, probably normal K-jarosite in which hydronium and sodium have substituted for part of the potassium.

A clear coating on part of a tailings clump from sample WA20-7 (2.1 m) proved to be a mixture of melanterite, $FeSO_4.7H_2O$, and ferrohexahydrite, $FeSO_4.6H_2O$. Melanterite is unstable and readily loses part of its water to form lower hydrates, especially the tetrahydrate. Minerals of this type also are readily soluble in water and reprecipitate on drying. Thus there is a strong possibility that the above sulphate minerals are not in their original hydration states. As is discussed in the next section, however, water-soluble iron sulphates are present in the tailings.

The main alteration product in most of the tailings is goethite, FeO(OH). In the tailings samples the mineral is always heterogeneous when viewed under the microscope, and thus no area was selected for microprobe analysis. Despite this optical heterogeneity, a few of the X-ray powder-diffraction patterns of the mineral gave normal cell dimensions and a diffraction-line sharpness indicative of good crystallinity. Other X-ray patterns gave poor patterns identifiable as goethite, but it is not certain

whether the inferior quality arises from poor crystallinity or inadequate X-ray material, or perhaps both. Lepidocrocite, FeO(OH), was detected in only two X-ray patterns. In contrast to goethite, lepidocrocite appears to be poorly crystalline and the identification, although fairly certain, is not absolute.

Native sulphur was identified in several X-ray powder patterns. The mineral was detected as an interstitial binder in the tailings clumps, but is more widespread as a component of the alteration rims around pyrrhotite. Despite the X-ray diffraction evidence of the presence of sulphur in the rims, the mineral could not be found as a discrete phase when these rims were examined under the scanning electron microscope. Energy dispersion analyses show that the alteration cores and rims have variable proportions of Fe and S, exactly as has been reported by Petruk and Pinard (1986). The X-ray diffraction evidence indicates that the alteration areas that are grey in reflected light consist of mixtures of iron oxide (mainly goethite) and sulphur. Despite this evidence, the additional presence of iron sulphate can be inferred from the microprobe results that are discussed below.

The alteration of pyrrhotite to extremely fine-grained intergrowths of pyrite and marcasite, both FeS_2, is well known and commonly takes the form of "bird's-eye" textures and minute veinlets. Altered pyrrhotite having this type of texture and mineralogy was observed only rarely in the tailings grains. Instead, the typical texture is to have marcasite formed at the margins of atoll-texture pseudomorphs after pyrrhotite (Fig. 3)

Microprobe analyses of three atoll-texture grains are given in Table 3. In reflected light the marcasite rims do not have the brightness of typical marcasite, and this lower reflectance suggests the possible presence of sub-

microscopic intergrowths with a non-sulphide phase or phases. This inference is supported by the low analytical totals, and also is supported by the observed gradation to duller, less metallic-looking rims. A similar gradation seems to extend to phases that are completely non-metallic in appearance.

Although X-ray patterns gave only goethite and sulphur as the identifiable non-sulphide components formed by pyrrhotite alteration, the additional presence of iron sulphate is indicated by microprobe analyses at wavelengths that discriminate "sulphate-type" versus "sulphide-type" sulphur. Table 3 gives the microprobe results obtained from dark, non-metallic cores associated with marcasite as shown in Figure 4. The analyses correspond roughly with a formula of $FeSO_4.nH_2O$ where n is less than 2. Compounds of this type, however, are not stable in vacuum or under the electron beam; this susceptibility to dehydration was mentioned previously in the description of ferrohexahydrite.

The analytical results, combined with the known presence of ferrous sulphates in the tailings not mounted in polisned sections, suggest that the components in the alteration rims and pseudomorphs are mixtures that consist predominantly of goethite, sulphur, and $FeSO_4.nH_2O$. The amount of ferrous sulphate is difficult to estimate from the polished sections because polishing normally involves contact with water, and thus there is an attendant loss of soluble sulphates. This type of loss probably accounts for the severe pitting noted to accompany the altered pyrrhotite in the polished sections. The polished section containing the analyzed iron sulphates (Table 3) was prepared using a non-aqueous medium. Addition of a drop of water to the polished surface rapidly led to severe pitting and the subsequent precipitation of abundant crystals of melanterite, $FeSO_4.7H_2O$.

Alteration trends

The colour variations (Table 2) show that, with one exception, there is a progressive downward darkening of the tailings. This colour variation coincides well with the microscopic observations of alteration intensity: the rust-brown upper samples represent a zone of strong oxidation, and the medium-brown samples represent an intermediate zone of moderate alteration that is gradational to a bottom zone of weak sulphide alteration.

The uppermost two samples at 0.3 m and 0.6 m evidently differed substantially in their original sulphide contents. Remnants of pyrrhotite were not seen in either sample, but only the near-surface one shows abundant outlines characteristic of pseudomorphs after pyrrhotite and pyrite. The few sulphide grains observed in the near-surface sample occur predominantly as small inclusions ($\leq$6 micrometres) protected by enclosure in silicates and magnetite; sulphides in the deeper sample are more abundant (Table 1) and are more common as free grains. In both samples goethite is abundant and, judging from the X-ray diffraction results, jarosite is concentrated in this zone. Goethite in the upper sample partly to completely rims all magnetite grains, generally as irregular and heterogeneous rinds that are only 1 to 2 micrometres wide, though widths of 5 to 10 micrometres are locally present. The majority of silicate grains also have goethite rims. Weaker alteration of the deeper sample at 0.6 m is indicated by its higher sulphide content and the presence of fewer goethite rims on magnetite. As well, goethite rims on silicates are less well developed in thickness and uniformity, and some silicate grains are free or almost free of rims.

The next deeper sample at 0.9 m differs significantly from those in the near-surface, strongly oxidized zone. The relative stability of magnetite is evident from its persistence and weak alteration in the strongly oxidized

zone; nevertheless, the sample at 0.9 m contains substantially less magnetite (Table 1) even though alteration is much weaker. This change is considered to reflect a variation in the components of the primary feed (i.e., original, unaltered tailings). The sample at 0.9 m contains abundant sulphides (Table 1), with pyrite predominating, and this depth marks the first appearance of numerous remnants of pyrrhotite. Iron oxide rims on silicates are almost absent, and alteration is largely confined to extensive replacement or complete pseudomorphism of the pyrrhotite. Minerals identified in the alteration rims are goethite, native sulphur, and lepidocrocite.

The next deeper group of samples at 1.2, 1.5 and 1.8 m has similarities in that both pyrrhotite and total sulphide contents are relatively high, and goethite rims on silicates are common. Goethite rims on magnetite are noticeably more pronounced in the sample from 1.5 m. The main indication of sulphide alteration is the partial replacement of pyrrhotite by rims containing mixtures of sulphur and goetnite. The deepest sample (1.8 m) also marks the approximate depth at which secondary marcasite appears as a readily recognized component of some of the rims on pyrrhotite. Petruk and Pinard (1986) detected jarosite in the sample from 1.8 m, and marcasite in the sample from 1.5 m.

The next deeper sample, at 2.1 m, shows a very large increase in original sulphides, expecially pyrite, and a readily observed decrease in the intensity of alteration. Goethite rims on silicates are extremely thin and occur sparingly, but the most distinctive indication of decreased alteration is that many pyrrhotite grains have only narrow alteration rims, and on many other grains these rims are incomplete. The adjacent, deeper

sample (WA20-8) is similar except that it shows both a slight but perceptible increase in goethite rims on silicates, and a decrease in the amount of marcasite in the rims around pyrrhotite.

The last two samples at the bottom of the tailings pile show the least amount of sulphide alteration. Pyrrhotite is abundant in both samples, and many grain edges are unaltered. Goethite is sparse and is largely confined to pyrrhotite replacement. These two samples show the best development of marcasite rinds on pyrrhotite.

Table 4 summarizes the alteration trends. Because of the difficulties in visually observing native sulphur, chemical analyses for elemental sulphur were obtained for four samples; the results (Table 4) show that sulphur is relatively low both in the strongly oxidized zone and in the least-altered bottom samples, but is present in substantial amounts in the intermediate alteration zone. These results fit well with the mineralogical data. Judging from the mineralogical observations it was anticipated that soluble iron sulphate would be highest in the intermediate zone and lowest in the strongly oxidized upper zone. The results obtained from five samples leached with water at room temperature are given in Table 5. Additional chemical analyses would be necessary to distinguish the contributions made by soluble calcium sulphate versus soluble iron sulphate; at this point it is only speculation that the high SO_4 value for sample WA20-2 (0.6 m) represents high calcium sulphate, whereas the rise in SO_4 values in the intermediate zone reflects increased iron sulphate.

CONCLUSIONS

1. Core WA20 through the Waite Amulet tailings shows substantial variations in the proportions of minerals that were discharged to the tailings. Despite these variations, which are quantitatively evident in the data of Petruk and Pinard (1986), there is good species uniformity in that pyrite plus pyrrhotite account for >95% of the original sulphides throughout the core.
2. Bassanite, $CaSO_4.H_2O$, occurs throughout the core. Large amounts of agricultural limestone were added to neutralize the tailings surface, and this provides a ready source of calcium to react with acidic sulphate solutions generated from the decomposition of sulphides.
3. Alteration of the tailings can be divided into three general zones: (1) a strongly oxidized near-surface zone depleted in sulphides; (2) an intermediate zone in which pyrrhotite, the sulphide least immune to alteration, has been strongly attacked but not obliterated; (3) a bottom zone of weak alteration in which pyrrhotite is largely preserved and alteration rims vary from narrow, to incomplete, to absent.
4. The principal alteration minerals are goethite, sulphur, and ferrous sulphates probably of the type $FeSO_4.nH_2O$. Other minerals identified are jarosite, lepidocrocite, and marcasite. Sulphur is abundant in the intermediate zone, and marcasite is most evident near the lowest part of the intermediate zone.
5. Polished sections of the tailings should be prepared using non-aqueous media in order to minimize losses of water-soluble phases.

ACKNOWLEDGMENTS

W. Petruk provided the samples used in this study and acted as technical reviewer of the manuscript. J.E. Dutrizac kindly arranged for the sulphur and sulphate determination by D.J. Hardy. Substantial assistance with the X-ray studies was provided by P. Carriere, and other technical help was given by D. LeBlanc and K. Besso.

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Figure 1. Tailings aggregate from the magnetic fraction of sample WA20-4 (1.2 m) showing a silicate-rich layer (dark, at top) overlying a layer rich in magnetite (m, medium grey) and sulphides (white). Lined white grains are partly altered pyrrhotite; unaltered white grains are pyrite. Some of the silicate grains are enclosed in thin rims of iron oxide. Reflected light, air; scale represents 0.25 mm.

Figure 2. Coarse silicates with sparse pyrite (py) and magnetite (m) in an aggregate from sample WA20-9 (2.7 m). Note contrast in grain size as compared with Figure 3.

Figure 3. Magnetite-rich aggregate from WA20-9, photographed at the same magnification as Figure 2, showing extensive alteration of pyrrhotite to atoll-texture pseudomorphs in which the white rims are marcasite. Reflected light, air; scale represent 0.25 mm.

Figure 4. SEM photograph showing pyrrhotite altered to marcasite rims and iron sulphate cores. Microprobe analyses for grains 2 and 3 are given in Table 3.

Table 1. Image analysis data for +37 m fractions from core WA20*

Sample	WA20-1	WA20-2	WA20-3	WA20-4	WA20-5	WA20-6	WA20-7	WA20-8	WA20-9	WA20-10
depth (metres)	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
Total silicates[1]	38.5	51.2	76.4	66.5	22.0	63.6	21.5	40.1	39.7	11.3
Magnetite[2]	46.8	43.6	10.4	13.5	37.9	7.5	12.7	19.4	18.6	7.5
Sulphides[3]	0.4	3.9	7.7	9.9	22.0	14.3	57.2	29.1	35.8	77.7
Goethite	14.2	1.4	5.1	8.1	5.8	7.3	2.8	6.3	3.1	1.1
Altered pyrrhotite	0.0	0.1	0.4	2.0	12.2	7.3	5.8	5.1	2.9	2.4
Magnetite + sulphides	47.2	47.5	18.1	23.4	59.9	21.8	69.9	48.5	54.4	85.2

*Condensed from Table 3 of Petruk and Pinard (1986). Quantities are in wt. %.

1. Quartz, K-feldspar, chlorite, amphibole and pyroxene
2. Reported as magnetite/hematite
3. Pyrite and pyrrhotite mainly
   Pyrrhotite > pyrite; all others have pyrite > pyrrhotite

Table 2. Colour variations of the hand-magnet separates of the +37 m fractions

Sample number	Depth, metres	A (non-magnetic fraction)	C* (strongly magnetic)	Colour group
WA20-1	0.3	rust-brown, lightest of all samples	darker; sparse in clumps	1
WA20-2	0.6	similar to 1A	similar to 1C	1
WA20-3	0.9	darker, medium brown	darker than 3A	2
WA20-4	1.2	darker than 3A and 3C	darker than 4A; brownish black	2
WA20-5	1.5	similar to 4A	darker than 4C	2
WA20-6	1.8	reversal in downward darkening trend; medium brown	slightly darker than 6A	3
WA20-7	2.1	similar to 5A, but greyer, less brown	darker than 7A, greyer than 5C	4
WA20-8	2.4	similar to 7A	similar to 7C	4
WA20-9	2.7	greyer, less brown than -7 and -8	fines almost black	4
WA20-10	3.0	brown colour fading and grey-black increasing	similar to 9C	4

Summary

Group 1: light medium-brown; aggregates (clumps) sparse and small
Group 2: lacks the ocherous, limonitic tint of Group 1; progressively darker in samples 3 to 4 to 5; clumps common in Groups 2, 3, 4
Group 3: reversal in that ocherous colour more intense and disrupts the progressive downward darkening trend
Group 4: characteristically greyer, less brownish than the upper samples

*moderately magnetic fraction have colours intermediate to those of A and C.

Table 3. Microprobe analyses of atoll-texture pseudomorphs of pyrrhotite in sample WA20-9

	Grain 1		Grain 2	Grain 3	Grain 2	Grain 3
	pyrrhotite, residual core	marcasite rim	marcasite rim	marcasite rim	dark core	dark core
wt. % Fe	60.4	43.1	43.0	43.0	33.4	33.6
S	37.9	46.5	49.7	50.6	20.6	17.9
	98.3	89.6	92.7	93.6	54.0	51.5

Analyst: D.R. Owens

Pyrrhotite and marcasite analyzed using "pyrrhotite 481" as a standard; sulphur values for the dark cores were obtained at the lower wavelength for S in a barite ($BaSO_4$) standard.

Table 4. General alteration trends in core WA-20

Sample numbers	Depth, metres	Alteration Features	Elemental S, wt. %
WA20-1, -2	0.3,0.6	strong oxidation of sulphides; negligible pyrrhotite; goethite abundant, some jarosite	0.22 in WA20-1
WA20-3	0.9	numerous pyrrhotite remnants; strong alteration of pyrrhotite to goethite and native sulphur	1.63
WA20-4, -5,-6	1.2, 1.5,1.8	pyrrhotite alteration less intense; marcasite rims start to appear at 1.8 m	2.54 in WA20-6
WA20-7, -8	2.1,2.4	weaker alteration of pyrrhotite -- some rims incomplete, but marcasite content higher	
WA20-9, -10	2.7,3.0	many pyrrhotite edges unaltered; homogeneity of marcasite reaches its peak in WA20-9	0.23 in WA20-10

Table 5. Chemical analyses of soluble sulphate in core WA20

Sample number	Depth, metres	Sample weight	Soluble SO_4, wt. %
WA20-2	0.6	2.9083 g	2.41
WA20-4	1.2	2.9971	1.45
WA20-6	1.8	2.9941	2.50
WA20-8	2.4	3.0433	2.30
WA20-10	3.0	2.9840	1.50

Samples slurried in 300 ml H_2O at room temperature for 30 minutes; solution filtered and a few drops HCl added to prevent Fe precipitation; SO_4 analyzed by ion chromatography. Analyst: D.J. Hardy.

1
2
py
3
4
3
2

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MINERALOGICAL AND CHEMICAL INVESTIGATION OF CORES FROM PIEZOMETRIC SITES IN WAITE AMULET TAILINGS, NORANDA, QUEBEC

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Process Mineralogy Section
Mineral Sciences Laboratory

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Tailings Management

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MINERALOGICAL AND CHEMICAL INVESTIGATION OF CORES FROM PIEZOMETRIC SITES IN WAITE AMULET TAILINGS, NORANDA, QUEBEC

by

J.L. Jambor

ABSTRACT

Polished-section microscopy of tailings samples from 31 piezometric sites in the Waite Amulet tailings pile shows that the amount of in-situ alteration of pyrrhotite and other sulphides is negligible. In several samples the bulk of the unaltered sulphide grains is accompanied by sparse, variously altered pyrrhotite grains which are interpreted to have been attacked by local surface oxidation during minor interruptions in the more than 30-year accumulation of the tailings pile. Chemical analyses of all of the tailings samples indicate that in most the water-soluble sulphate fraction is less than 1 wt % SO_4, and most of this sulphate is bound as $CaSO_4.nH_2O$. Sulphate which is not water-soluble exceeds 0.3 wt % SO_4 in only 3 samples, and in 2 of these the presence of jarosite has been confirmed by X-ray powder-diffraction patterns. The average value of 0.27 wt % elemental sulphur in the 31 samples is interpreted to be representative of background sulphur rather than an indication of alteration-derived sulphur.

INTRODUCTION

The Waite Amulet minesite, about 20 km north of Noranda, Quebec, has 5.9 million tonnes of sulphide-rich tailings derived from ten orebodies mined in the area from 1929 to 1962. The tailings are 2 to 15 m thick and are in an elevated 41 hectare dam that is undergoing extensive hydrogeochemical investigations to determine the character, sites, and a regulating factors of acid generation (Siwik, 1986). This 5-year research program, begun in 1985, is part of the national Reactive Acid Tailings Study (RATS). Noranda Research centre and CANMET are joint participants in the Waite Amulet study.

To assist in the mineralogical characterization of the Waite Amulet tailings, a series of samples from core WA-20 was examined by the Process Mineralogy Section (Petruk and Pinard, 1986; Jambor, 1986). The hole site is at the steeply sloping edge of the tailings dam and may not be representative of the alteration profile for the main part of the tailings pile. Although additional profiles will be studied as the program advances, priority at the current stage of the investigation was given to a mineralogical examination of samples collected at piezometric sites.

SAMPLE PREPARATION

According to Siwik and Dave (1987), core samples of the tailings were obtained using a hollow-stem auger with a 10.8 cm inner diameter, into which was fitted a split-barrel sampler 1.5 m long and 8.25 cm in diameter. For the present study 31 core samples, frozen and sealed in plastic bags, were received from Noranda Research Centre, Pointe Claire, Quebec, on November 20, 1986. Information about drill sites and depth of core collection was not provided. The cores, labelled A-1 to A-31, were temporarily stsored in a freezer at CANMET prior to drying. Average sample weight was about 1 kg.

For drying, each sample was removed from its plastic bag and allowed to thaw at room temperature. Subsequent air-drying was accelerated by spreading the pulp over an area of about 0.5 m in diameter on a base of thick brown paper. As drying progressed the pulp was mixed repeatedly and larger lumps were broken to ensure maximum surface exposure. Most samples dehydrated rapidly, but up to 5 days of drying were required for clay-rich or organic-rich material. No significant discoloration or bleaching of the paper base was observed during or at the end of the drying period, thus indicating that the moisture from the samples was unreactive. Likewise, no significant discoloration of the dried tailings pulps was observed. None of the original, uncrushed cores contained megascopic indications of strong oxidation; likewise, no strongly discolored layer indicative of iron oxide-hydroxide alteration was observed in any sample, though a few "iron-stained" layers, 2 to 3 mm thick, were noted to occur erratically.

The air-dried samples were crushed by hand, but not ground, to pass through a 36 mesh Tyler screen (aperture size 425 micrometres). The relative ease with which the crushing and sieving were accomplished was noted and is summarized in Table 1. A small portion of the +36 mesh residual material was collected and bottled as coarse-fraction reference material. Cohesion of the samples was greatest for those noted to contain clay or fine-grained, clay-like textures, and in general the megascopic appearances correlated extremely well with the textures observed in the subsequent microscopic examination (Table 1).

The -36 mesh fraction was boxed, and subsequently each sample was again spread on paper, rolled, and cone-and-quartered. A small fraction from each

quarter was combined and bottled to use for polished sections, and the remainder of the opposite quarters was combined and bagged. One split was submitted for chemical analysis, and the other was retained as surplus reference material.

Twenty-eight polished sections of the -36 mesh samples were prepared using non-aqueous media. Cores A-10, A-11, and A-31 consist wholly of clay-rich material devoid of sulphides, and these samples therefore were not examined microscopically. The clay-rich cores are well-bedded and presumably are from the basal clay zone, 2 to 20 m thick, upon which the tailings were deposited.

Reconnaissance microscopic examination of the 28 polished sections showed that in many the sulphides are very fine-grained, sparse, or both, and that alteration of the sulphides is extremely weak. Because pyrrhotite is the mineral most susceptible to alteration, an effort was made to obtain a higher yield of the coarser particles of this mineral. Therefore, portions of the fine-grained samples, which already had been screened to -36 mesh, were rescreened to -270 mesh (aperture size 53 micrometres) and the fines were rejected. The +270 mesh fraction was spread on paper, traversed with a hand magnet to collect the most strongly magnetic fraction, and these magnetic concentrates were mounted in polished sections. Twenty of the 28 samples were treated in this manner, and only 4 failed to show a significant magnetic response; for the 4 non-responsive samples, coarse lumps from the +36 reference material were hand-picked and mounted in polished sections. In total, therefore, 48 polished sections of the tailings were examined.

RESULTS

Hand-magnet separations

Screening to remove the fines, and subsequent hand-magnet concentration, proved to be an effective method of increasing the abundance and coarseness of pyrrhotite in most of the samples (Fig. 1-4). The few samples that did not respond favourably to this technique were found to consist of fine-grained sulphides dispersed in a fine-grained matrix; coarser particles were absent in the primary material, and thus no concentration was possible.

Textures

Well-developed sulphide-silicate layering was conspicuous in several of the original cores. The layering reflects both a variation in particle sizes, and variations in mineral contents. For example, the layering in some samples was evident because fine-grained beds alternated with coarser-grained beds; in other samples the layering was made conspicuous by the concentration of yellow sulphides into specific beds amidst equigranular material. The layering is considered to be of primary derivation in that it arose from fluctuations in the constitutents added, or unintentionally sorted, during progressive accumulation of the tailings pile.

The samples used for the polished sections and for the chemical analyses invariably represent a blend or homogenization of many layers. Nevertheless, on the basis of microscopic observations of the polished sections, the sulphide-magnetite components of the tailings were classified as fine-grained, intermediate, and coarse (Table 2). The classification is not considered to be particularly significant, but it serves not only to illustrate the very large

variation in grain sizes amongst the samples from the piezometric sites, but also provides a contrast with WA-20 core samples (Jambor 1986), none of which would be categorized as fine-grained in this system.

Numerous examples of the textural categories are illustrated in Figures 1 to 4. The fine-grained and coarse-grained textures represent the opposite extremes of the classification, and thus the intermediate category is the broadest and has the greatest diversity in textures. For example, some samples designated as intermediate consist mainly of sulphides of a medium grain size (sample 6, Fig. 2), whereas others have predominantly fine-grained sulphides mixed with scattered coarse grains (samples A-26 and A-27, Fig. 4). These and other variations would permit additional textural subdivisions to be made, but this aspect was not pursued because no ensuing correlation with alteration could be perceived.

Microscopic observations of sulphides and alteration

Microscopic studies of the polished sections in reflected light revealed that the principal sulphide minerals are pyrite and pyrrhotite, and that most sections also contain several grains of chalcopyrite that are typically in locked intergrowths rather than free. Magnetite occurs in variable amounts, either as a major or minor constituent, and only traces of other minerals such as sphalerite, stannite, and native bismuth are present. These sulphide-magnetite and trace constituents are similar to the assemblages noted in core WA-20 (Petruk and Pinard 1986; Jambor 1986), but the samples from the piezometric sites show more clearly that the variations in mineral proportions simply reflect the primary layering.

Without exception the most distinctive feature of the tailings from the piezometric sites is the absence of significant alteration. In all samples the grain edges of pyrrhotite, which is the mineral most susceptible to alteration, are typically sharp and unreplaced; in several samples, however, scattered pyrrhotite grains with altered rims occur amidst the unaltered grains. These alteration rims indicate that the pyrrhotite was attacked only moderately rather than strongly, and the erratic distribution of the partly altered grains suggests that the alteration was confined to minor layers rather than being pervasive. Similarly, a few goethite rims were observed, but these are extremely narrow and also of erratic distribution. Grain-boundary alterations of pyrite, magnetite, and chalcopyrite are negligible. Table 3 gives the microscopically observed alteration features. Although the pyrrhotite:pyrite:magnetite ratios were estimated for each of the polished sections, these ratios are irrelevent because of the negligible degree of alteration.

X-ray diffractometer scans of clay samples A-10, A-11, and A-31 showed that these samples consist mainly of quartz, plagioclase, chlorite, and muscovite. Calcite was detected in sample A-11. Samples A-10 and A-11 effervesced extremely vigorously when acid was applied, but no reaction was obtained from sample A-31.

Chemical analyses

The principal alteration minerals detected in core WA-20 (Jambor 1986) are goethite, lepidocrocite, marcasite, jarosite, native sulphur, soluble iron sulphates of the type $FeSO_4.nH_2O$, and simple calcium sulphates of the type $CaSO_4.nH_2O$. Because these alteration products are extremely fine grained and

difficult to estimate quantitatively, an analytical chemical approach was deemed to be the most useful in attempting to quantify the abundances of some of the various alteration minerals. The assumptions are that the water-soluble fraction of the tailings contains the $FeSO_4.nH_2O$ and $CaSO_4.nH_2O$ minerals, that the analyses for elemental sulphur reflect the presence of native sulphur, and that the sulphate fraction which is not water-soluble is bound in jarosite. The chemical results obtained from samples of previously studied core WA-20 correlated well with the mineralogical studies, both showing well-defined trends in terms of the intensity of alteration.

The results of the chemical analyses of the core samples from the piezometric sites are given in Table 4. A 2-g split agitated in 100 ml of water was used for the water-soluble sulphate, calcium, and iron determinations. A second 2-g split was used for the determination of total sulphate, and a separate 1-g split was analyzed for elemental sulphur. Details of the preliminary chemical tests and the subsequent analytical procedures are given by Hole et al. (1987).

In addition to the chemical results, Table 4 shows the calculated amounts of SO_4 required to use up all of the Ca and Fe in the water-soluble fraction; additional SO_4 not used by the Ca and Fe compounds is tabulated as Remnant SO_4. In most samples the Remnant SO_4 values are fairly low, but in 4 samples (A-2, A-26, A-27, A-28) the values exceed 1 wt. %. It was thought that these samples might contain significant amounts of Na, K, Cu, Mg, or Al soluble salts, but specific analyses for these elements has shown their abundances to be low (Table 5).

The last column in Table 4 gives the value obtained by subtraction of the wt. % water-soluble sulphate from that of total sulphate. This value represents the less soluble compounds such as jarosite. Although the value is generally low, it exceeds 0.3 wt. % in samples A-9, A-17, and A-30. The possible presence of jarosite in samples A-9 and A-17 was indicated by minor oxidation discoloration noted both megascopically and microscopically, and confirmation of the presence of this mineral was obtained by X-ray powder diffracion patterns. No jarosite was observed in sample A-30.

INTERPRETATIONS

All of the samples examined in this study are from below the water table, and all are devoid of significant alteration. The presence of sparse, altered pyrrhotite grains amidst a preponderance of fresh, unaltered grains is an incompatible association that could be interpreted as arising from (a) contamination, or (b) local oxidation. Contamination arises because altered tailings from higher in the hole coat the core barrel and are incorporated as a rind on the main core sample. This effect was very pronounced on two samples of newly received core (not from the piezometric sites and not yet studied), but the contamination was obvious only because of the distinct colour differences between the rind and the main core. This feature was not noticed in the cores from the piezometric sites. In the case of alternative (b), i.e., local oxidation, it was mentioned previously that strongly oxidized cores is absent, but that thin "iron-stained" layers were noted to occur erratically. The thinness of the layers and their erratic presence suggests that each was a surface feature that originated during a minor hiatus in the accumulation of the tailings pile.

These local paleosurfaces were buried subsequently and oxidation ceased. The seemingly incompatible association of altered and unaltered pyrrhotite grains results from blending of the total core sample, thus incorporating the minor, weakly altered zones among the largely unaltered bulk sample.

The second item that merits interpretation is the results of the chemical analyses. In previously studied core WA-20 (Jambor 1986), the calcium sulphate minerals were assumed to have formed from sulphate solutions reacting with calcium derived from lime added to neutralize the surface of the tailings pile. A similar source for the calcium sulphate in the samples from the piezometric sites is possible, but is entirely speculative. An alternative source for calcium is in the reagents added to the flotation circuits; according to Siwik and Dave (1987), the amount of $Ca(OH)_2$ added to the zinc flotation circuit was 0.329 lbs/ton.

The ultimate disposition of other compounds used in the flotation circuits remains one of the major unknown entities in the study of the tailings chemistry. Chief among the added cations is sodium. For example, sodium sulphide and soda ash consumption totalled more than 3.4 lbs/ton in the Waite Amulet copper flotation circuit (Siwik and Dave 1987). Presumably much of this sodium was deposited with the tailings, but no specific mineral carrier has been identified. Similarly, no specific mineral (i.e., native sulphur) has been identified to account for the analytical values obtained for elemental sulphur (Table 4). Certainly the elemental sulphur cannot be attributed to in-situ alteration of pyrrhotite or other sulphides. According to J.E. Dutrizac (oral communication, 1987), elemental sulphur values of the magnitude reported here

are not unusual even for unaltered sulphide-rich samples. It also is possible that sodium sulphide, used as a flotation reagent, contributes to the analytical sulphur values. Thus, the values obtained here for elemental sulphur are interpreted to be principally an indication of "background sulphur" rather than an indication of in-situ alteration.

CONCLUSIONS

1. Microscopic studies of polished sections of the tailings samples from piezometric sites indicate that all samples have negligible amounts of alteration in terms of total sample weight or volume. The presence of sparse altered grains of pyrrhotite amidst unaltered grains is attributed to local surface oxidation that occurred during minor interruptions in the accumulation of the tailings.
2. Chemical analyses indicate that the water-soluble sulphate fraction is low in most samples, and most of this sulphate is bound as $CaSO_4.nH_2O$. The low iron contents of the water-soluble fraction are in accord with the negligible degree of alteration of the sulphides.
3. The fraction of total sulphate that is not water-soluble is low and exceeds 0.3 wt. % in only 3 samples. Most of this relatively insoluble sulphate probably occurs as jarosite, the presence of which was confirmed in 2 of the 3 samples.
4. Three of the cores consist of layered clay that is assumed to be from the floor upon which the tailings were deposited. Two of these clay samples are calcite-rich, thus indicating that the clay is a barrier which is relatively impermeable to penetration by the acid-rich tailings solutions.

5. Contents of elemental sulphur in the samples range from less than 0.01 wt. % to 0.85 wt. %, and the average is 0.27 wt. %. These values are much higher than expected considering the negligible degree of sulphide alteration. The highest sulphur value occurs in a jarosite-bearing sample, suggesting a possible correlation with alteration. Nevertheless, from the results as a whole it is concluded that the elemental sulphur values obtained for this series of samples are more representative of "background sulphur" than of alteration-derived sulphur.

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Fig. 1. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite (py) and pyrrhotite (po) appear as white to light grey particles; darker grey is magnetite (m).

Sample A-1, magnetic separate. Texture: fine-grained, low sulphide content. Magnetic concentration did not produce a coarser grained sulphide fraction.

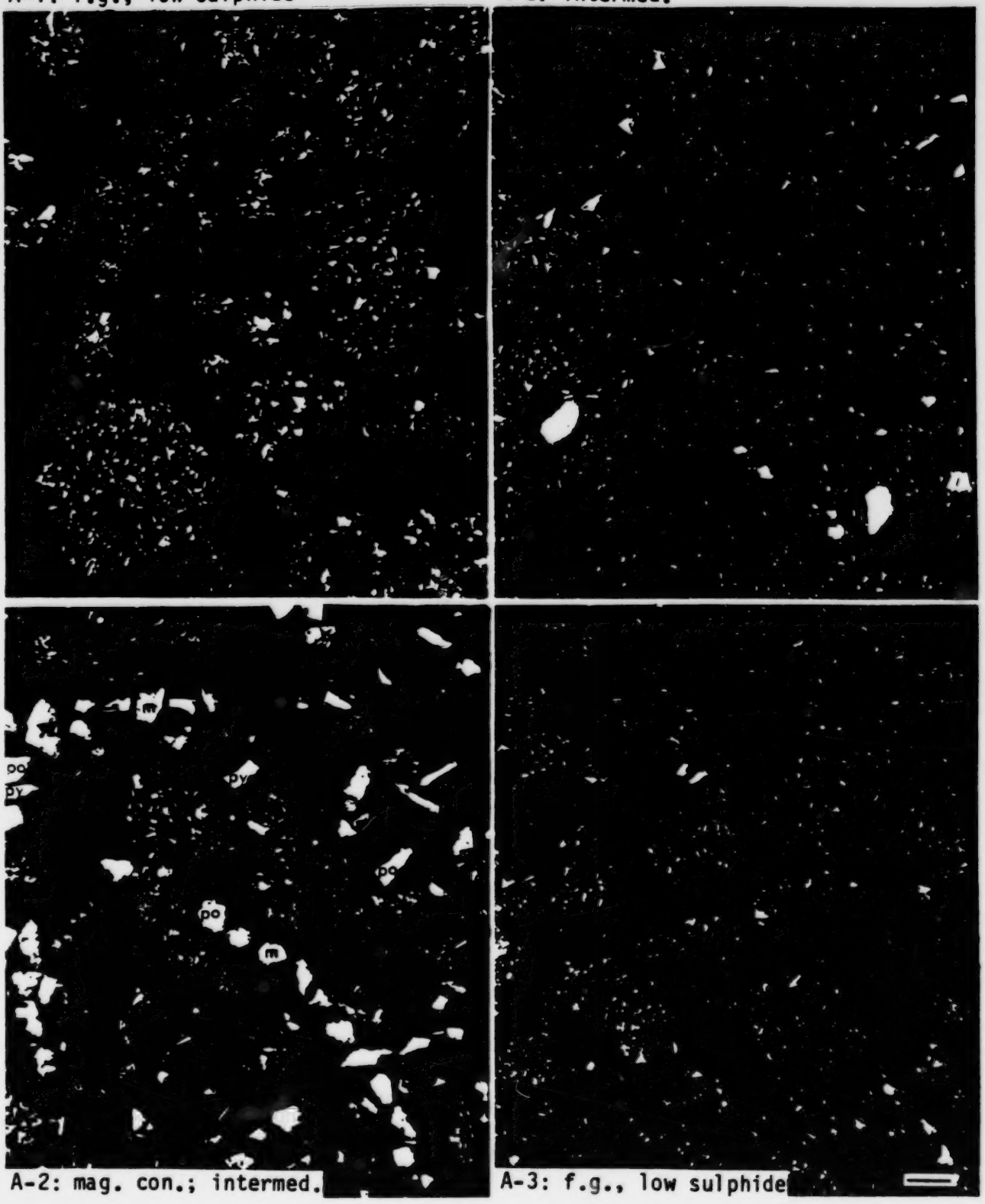
Sample A-2, original fraction. Texture: intermediate; mainly fine-grained sulphides with sparse coarse grains.

Sample A-2, magnetic fraction. Texture: intermediate, coarse grains and clumps containing predominantly medium-grained sulphides have reported to the magnetic concentrate.

Sample A-3, magnetic fraction. Texture: fine-grained, low sulphide content. Magnetic concentration was ineffective.

A-1: f.g., low sulphide

A-2: intermed.



A-2: mag. con.; intermed.

A-3: f.g., low sulphide

Fig. 1

Fig. 2. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-4, magnetic separate. Texture: fine-grained sulphides and low sulphide content. Magnetic concentration ineffective.

Sample A-5, original fraction. Texture: intermediate; mainly coarse and medium-grained sulphides.

Sample A-6, original fraction. Texture: intermediate, with sparse coarse sulphides amid medium-grained sulphides.

Sample A-6, magnetic separate. Texture: coarse sulphides and abundant coarse magnetite (m).

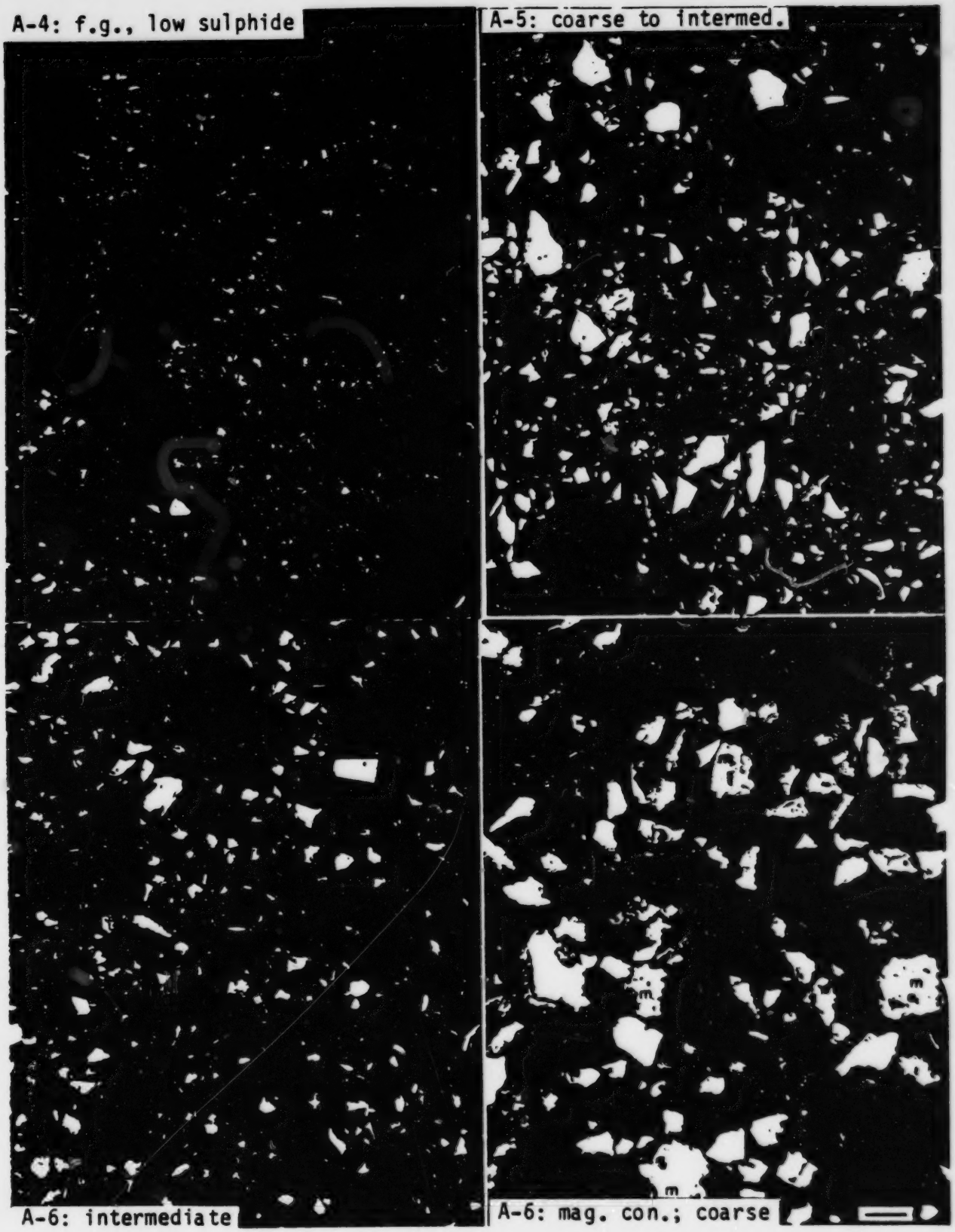

A-4: f.g., low sulphide
A-5: coarse to intermed.
A-6: intermediate
A-6: mag. con.; coarse

Fig. 2

Fig. 3. Photographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-21, original fraction. Texture: coarse-grained.

Samplel A-24, original fraction. Texture: intermediate, with sulphides variable from fine-grained to coarse.

Sample A-22, original fraction. Texture: intermediate, with sulphides predominantly fine-grained, but variable (contrast with sample A-4, Fig. 2).

Sample A-22, magnetic separate. Texture: intermediate.

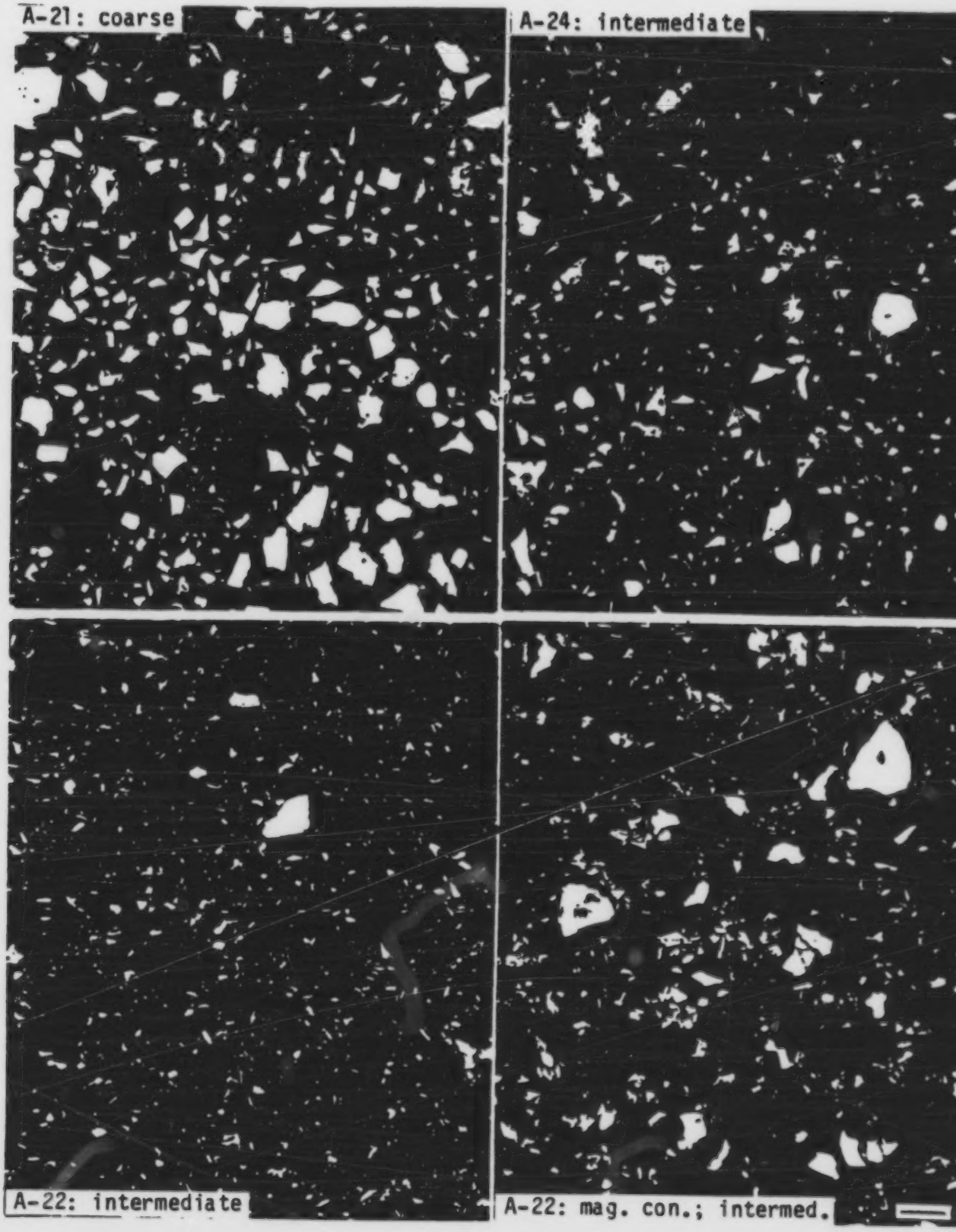

A-21: coarse
A-24: intermediate
A-22: intermediate
A-22: mag. con.; intermed.

Fig. 3

Fig. 4. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-26, original fraction. Texture: intermediate, mainly fine- and medium-grained with few coarse grains.

Sample A-26, magnetic separate. Texture: intermediate to coarse; concentration was effective.

Sample A-27, original fraction. Texture: intermediate.

Sample A-29, magnetic separate. Texture: fine-grained, low sulphide contents, and ineffective concentration.

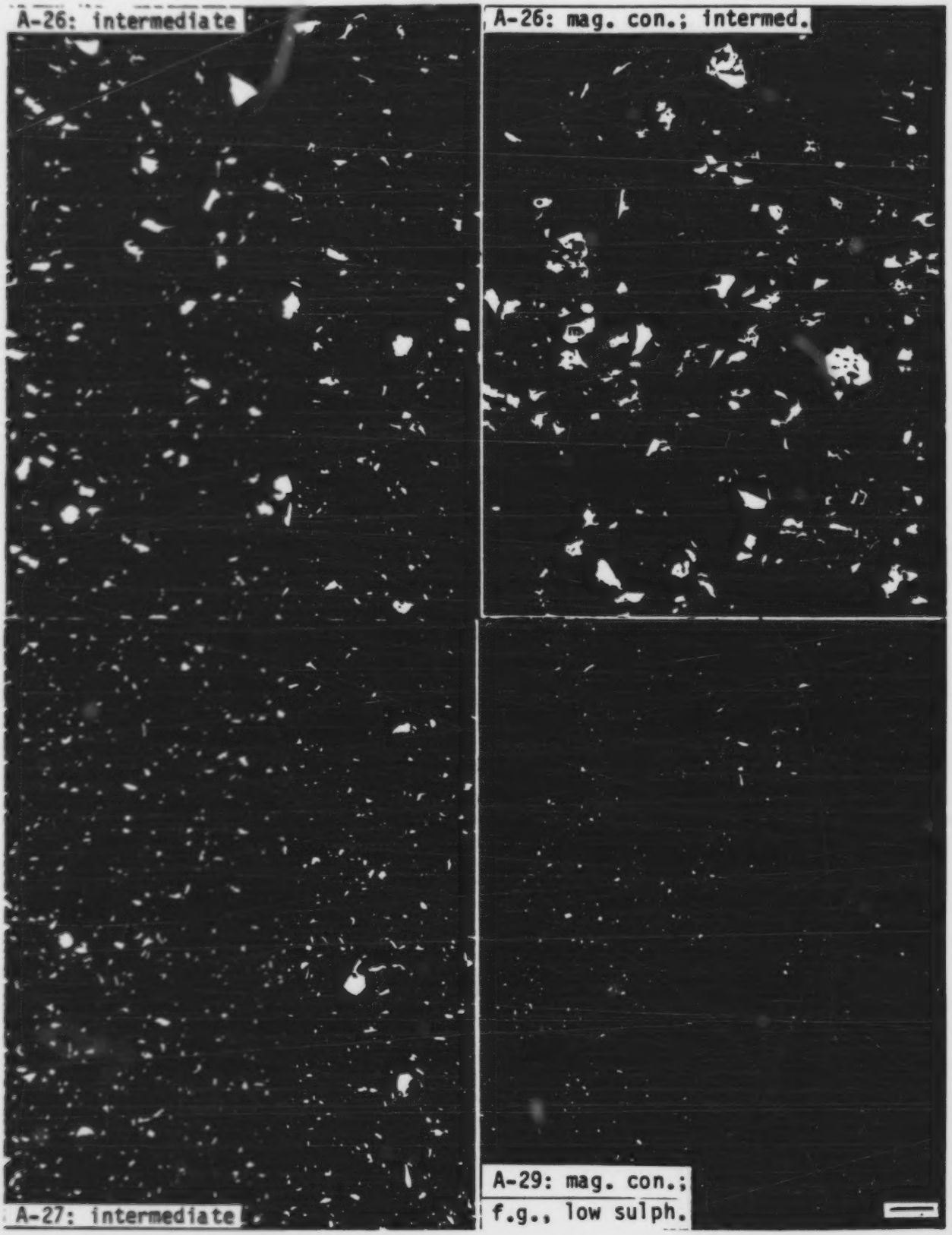

A-26: intermediate
A-26: mag. con.; intermed.
A-27: intermediate
A-29: mag. con.; f.g., low sulph.

Fig. 4

Table 1. General features of Waite Amulet core samples A-1 to A-31

Sample Number	Megascopic Features; Crushing and Sieving Properties	Microscopic Character
A-1	partly clay-like*; lumps crushed with only moderate difficulty	all fine-grained (Fig. 1)
A-2	almost clay-like; lumps persistent, crushing difficult	mainly fine-grained (Fig. 1)
A-3	almost clay-like; lumps persistent, crushing difficult	fine-grained (Fig. 1)
A-4	almost clay-like; crushed easily	fine-grained (Fig. 2)
A-5	well-layered, high sulphide content; crushed easily	coarse to medium-grained (Fig. 2)
A-6	easily broken and sieved	coarse to medium-grained sulphides (Fig. 2)
A-7	easily broken and sieved	abundant coarse sulphides
A-8	easily broken and sieved	abundant coarse sulphides
A-9	broken and sieved with moderate ease, but some clumps	intermediate grain sizes
A-10	bedded clay; very tough	
A-11	bedded clay; very tough	
A-12	well-layered, coarse-grained sulphides; sieved with great ease	coarse sulphides
A-13	crushed and sieved with ease	coarse sulphides
A-14	crushed and sieved with ease	coarse sulphides
A-15	crushed and sieved with ease	coarse sulphides
A-16	more than 90% organic, mainly a log or old timber	coarse to medium-grained sulphides
A-17	crushed and sieved with ease	coarse to medium-grained sulphides
A-18	abundant organic (peat-like) material; partly clay-like and low in sulphides; difficult to sieve, traces of iron-oxide staining	coarse to medium sulphides, but very sparse
A-19	abundant sulphides; crushed and sieved with ease	coarse sulphides

Table 1. General features of Waite Amulet core samples A-1 to A-31 (cont'd)

Sample Number	Megascopic Features; Crushing and Sieving Properties	Microscopic Character
A-20	abundant sulphides; crushed and sieved with ease	coarse sulphides
A-21	abundant sulphides; crushed and sieved with ease	coarse sulphides (Fig. 3)
A-22	abundant peat, twigs, but sulphides easily sieved	medium-grained sulphides (Fig. 3)
A-23	crushed and sieved easily	coarse sulphides
A-24	sieved very easily; no residual clumps	coarse to medium-grained sulphides (Fig.3)
A-25	similar to A-24	coarse sulphides
A-26	somewhat clay-like, but sieved easily	coarse to fine-grained sulphides (Fig. 4)
A-27	similar to A-26	similar to A-26 (Fig. 4)
A-28	fine-grained, black, almost muddy; crushed and sieved easily	mainly sparse, fine-grained sulphides
A-29	similar to A-28	similar to A-28, but sulphides more abundant (Fig. 4)
A-30	black, muddy, well-layered, but crushed and sieved without difficulty	fine-grained, sparse sulphides
A-31	bedded clay; very tough	

*Clay-like refers to the fine-grained texture rather than to the mineral constituents. Sample A-10, A-11, and A-31, however, are clays rather than merely clay-like.

Table 2. Microscopic textures of Waite Amulet tailings and magnetic concentrates

Sample Number	Textural Classification	General Microscopic Features	Magnetic Fraction
A-1	fine	fine-grained, low sulphide; mainly silicate gangue peppered with sulphides (Fig.1)	no change
A-2	intermediate	mainly fine-grained with scattered coarser grains (Fig. 2)	coarser sulphides increas appreciably (Fig. 2)
A-3	fine	fine-grained, low sulphide (Fig. 1)	fine-grained with sparse sulphide-magnetite grain 30-100 micrometres acros
A-4	fine	similar to A-3 (Fig. 2)	fine-grained with sparse coarse grains
A-5	coarse to intermediate	abundant sulphides, coarse to medium grain sizes (Fig. 2)	not obtained
A-6	intermediate	predominantly medium-grained, free grains (Fig. 2)	coarse (Fig. 2)
A-7	coarse to intermediate	variable, predominantly coarse to medium grains; sulphide content only moderate	coarse
A-8	coarse to intermediate	mainly coarse grains, but clumps with fine-grained sulphides are common	coarse
A-9	intermediate	mainly clumps with medium-grained and fine-grained sulphides; coarse free grains common	intermediate
A-10	clay		
A-11	clay		
A-12	coarse	abundant coarse sulphides	not obtained
A-13	coarse	abundant coarse and medium-grained sulphides	predominantly coarse
A-14	coarse	moderately abundant coarse to medium-grained sulphides	not obtained
A-15	coarse	abundant coarse and medium-grained sulphides	coarse
A-16	coarse	abundant coarse and medium-grained sulphides	coarse
A-17	coarse	abundant coarse and medium-grained sulphides	not obtained

Table 2. Microscopic textures of Waite Amulet tailings and magnetic concentrates (cont'd)

Sample Number	Textural Classification	General Microscopic Features	Magnetic Fraction
A-18	coarse	coarse free grains, many 90-100 micrometres across	coarse
A-19	coarse	coarse sulphides, abundant	coarse
A-20	coarse	coarse sulphides, abundant	not obtained
A-21	coarse	coarse sulphides, abundant (Fig. 3)	coarse
A-22	intermediate	predominantly fine to medium-grained sulphides; sulphides abundant (Fig. 3)	intermediate (Fig. 3)
A-23	intermediate	variable from fine-grained to coarse; sulphides abundant, clumps common	not obtained
A-24	intermediate	abundant, medium to coarse (Fig. 3)	not obtained
A-25	coarse	predominantly coarse grains, moderately abundant	not obtained
A-26	intermediate	coarse to fine-grained sulphides, only moderately abundant (Fig. 4)	intermediate to coarse (Fig. 4)
A-27	intermediate	coarse to medium-grained, abundant (Fig. 4)	intermediate
A-28	fine	mainly fine-grained; sulphide content relatively low; sparse coarse grains	intermediate
A-29	fine	mainly fine-grained; sulphide content relatively low (Fig. 4)	no change
A-30	fine	mainly fine-grained with low sulphide content	fine (some coarse grains
A-31	clay		

Table 3. Microscopic observations of alteration in tailings from piezometric sites

Sample Number	General Alteration Features	Alteration Intensity
A-1	pyrrhotite edges sharp, intact	negligible
A-2	-	negligible
A-3	thin, grey, partial rims on a few pyrrhotite grains	negligible
A-4	-	negligible
A-5	rim alteration of a few pyrrhotite grains	negligible
A-6	-	negligible
A-7	-	negligible
A-8	-	negligible
A-9	some clumps have pyrrhotite grains with altered rims; local orange (jarosite?) alteration in silicates[1]	local alteration, overall negligible[2]
A-10	clay; carbonate-rich	-
A-11	clay; carbonate-rich	-
A-12	sparse alteration rims on pyrrhotite	negligible
A-13	traces of rim alteration on pyrrhotite	negligible
A-14	a few pyrrhotite grains moderately altered, but otherwise nearly all are fresh	negligible
A-15	several pyrrhotite grains with altered rims; traces of goethite, as rims 1-2 micrometres wide, on silicates	local alteration, overall negligible
A-16	-	negligible
A-17	a few pyrrhotite grains with altered rims	negligible
A-18	similar to A-15	local alteration, overall negligible
A-19	numerous pyrrhotite grains with altered rims 1 to 3 micrometres wide; faint traces of goethite rims on silicates	extremely weak
A-20	traces of rim alteration	negligible

Sample Number	General Alteration Features	Alteration Intensity
A-21	similar to A-19	negligible
A-22	traces of rim alteration	extremely weak
A-23	sparse rims on pyrrhotite; traces of goethite	negligible
A-24	-	negligible
A-25	-	negligible
A-26	traces of rim alteration of pyrrhotite	negligible
A-27	-	negligible
A-28	a few pyrrhotite grains weakly to moderately altered	negligible
A-29	-	negligible
A-30	traces of rim alteration	negligible
A-31	clay sample	negligible

1. Jarosite subsequently confirmed by X-ray powder diffraction patterns.
2. Chemical analyses (Table 4) show this sample to be the highest in sulphate.

Table 4. Chemical analyses of tailings from piezometric sites, and calculated distribution of SO_4

Sample No.	pH	Chem. Anal., Water-Soluble Fraction*			Calculated Distributions (wt%)			Chem. Anal., Whole Sample**		Total SO_4 Minus Water-soluble SO_4**
		Fe	Ca	SO_4	SO_4 as $CaSO_4$	SO_4 as $FeSO_4$	Remnant SO_4	elemental S	total SO_4	
A-1	6.7	<0.01	0.35	1.08	0.84	0.0	0.24	0.52	1.20	0.12
A-2	4.3	0.06	0.31	2.07	0.74	0.10	1.23	0.61	2.28(2)	0.21
A-3	7.5	<0.01	0.55	1.62	1.32	0.0	0.30	0.32	1.71(2)	0.09
A-4	7.9	<0.01	0.37	1.14(2)	0.89	0.0	0.25	0.47	1.14(2)	0.00
A-5	8.3	<0.01	0.13	0.36	0.31	0.0	0.05	0.38	0.39(2)	0.03
A-6	8.4(2)	<0.01(2)	0.12(2)	0.42(2)	0.29	0.0	0.13	0.32	0.42(2)	0.00
A-7	8.7	<0.01	0.10	0.33	0.24	0.0	0.09	0.30	0.36	0.03
A-8	5.5(4)	<0.01(4)	0.27(4)	0.78(4)	0.65	0.0	0.13	0.36	1.05(2)	0.27
A-9	4.3(2)	0.06(2)	0.44(2)	1.98(2)	1.05	0.10	0.83	0.85(2)	2.40(4)	0.42
A-10	8.8(2)	0.06(4)	0.10(4)	<0.03(2)	-		-	0.31(2)	0.03(2)	0.03
A-11	9.0(2)	0.08(4)	0.15(4)	<0.03(2)	-	-	-	0.16	0.03(2)	0.03
A-12	7.6	<0.01	0.07	0.21	0.17	0.0	0.04	0.15	0.24(2)	0.03
A-13	8.5	<0.01	0.14	0.33	0.33	0.0	0.00	0.08	0.33	0.00
A-14	8.7	<0.01(2)	0.08(2)	0.18(2)	0.18	0.0	0.00	0.08	0.27	0.09
A-15	7.9	<0.01	0.09	0.27	0.22	0.0	0.05	0.35	0.33	0.06
A-16	4.6	0.02	0.14	0.54	0.34	0.03	0.18	0.43	0.60(2)	0.06
A-17	4.7(2)	0.09(2)	0.46(2)	1.62(2)	1.10	0.15	0.37	0.14	1.95(2)	0.33
A-18	6.4	<0.01	0.04	0.27	0.10	0.0	0.17	<0.01	0.33	0.06
A-19	4.9	0.09(3)	0.15(3)	0.78(4)	0.36	0.15	0.27	0.21	0.90(2)	0.12
A-20	4.9(2)	0.01(2)	0.19(2)	0.63(2)	0.46	0.02	0.15	<0.01	0.66(2)	0.03
A-21	4.6	0.08	0.03	0.36	0.07	0.14	0.15	0.36	0.39	0.03
A-22	4.4	0.17	0.15	0.81	0.36	0.29	0.16	0.40	1.02	0.21
A-23	6.9	<0.01	0.15	0.48	0.36	0.0	0.12	0.26	0.51(2)	0.03
A-24	6.9	<0.01	0.22	0.66	0.53	0.0	0.13	0.21	0.66(2)	0.00
A-25	6.1	<0.01	0.06	0.24	0.14	0.0	0.10	0.24	0.27(2)	0.03
A-26	4.8(2)	<0.01(2)	0.23(2)	1.08(2)	0.55	0.0	0.53	0.59(2)	1.11(2)	0.03
A-27	6.1	<0.01	0.44	1.26	1.05	0.0	0.21	<0.01	1.26(2)	0.00
A-28	8.1	<0.01	0.40	1.05	0.96	0.0	0.09	<0.01	1.20(2)	0.15
A-29	7.9	<0.01	0.36	0.81	0.81	0.0	0.00	<0.01	0.93(2)	0.12
A-30	7.7(4)	<0.01(4)	0.30(4)	0.63(4)	0.63	0.0	0.00	0.19	1.08(2)	0.45
A-31	7.0(4)	0.02(4)	<0.01(4)	0.03(4)	-	0.03	0.00	<0.01	0.03(3)	0.00

*Water-soluble at room temperature; values are in wt %.
**Wt %. Numbers in parentheses refer to replicate determinations of separate splits.

Table 5. Chemical analyses of samples containing excess water-soluble sulphate*

Sample	Original (wt %)				New Analysis (wt %)							
No.	pH	Fe	Ca	SO_4	pH	Fe	Ca	SO_4	Na	K	Cu	Mg	Al
A-2	4.3	0.06	0.31	2.07	4.1	0.12	0.45	2.40	<0.01	0.02	0.03	0.06	0.03
A-26	4.8	<0.01	0.23	1.08	4.4	0.04	0.26	1.11	<0.01	0.09	<0.01	0.06	<0.01
A-27	6.1	<0.01	0.44	1.26	5.5	<0.01	0.42	1.29	<0.01	0.04	<0.01	0.03	<0.01
A-28	8.1	<0.01	0.40	1.05	7.6	<0.01	0.50	1.32	0.01	0.02	<0.01	0.09	<0.01

*Refers to excess water-soluble sulphate that cannot be accounted for in terms of simple calcium sulphate or ferrous sulphate compounds.

APPENDIX B

TERRAQUA INVESTIGATIONS LTD.

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HYDROGEOLOGICAL SAMPLING AND INSTRUMENTATION OF THE WAITE AMULET TAILINGS 1986, FIELD SEASON

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Reference TA8616

March 1987

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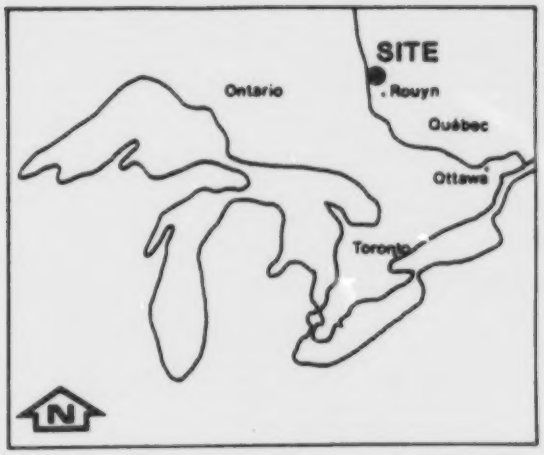
1.0 INTRODUCTION

1.1 Summary of Previous Work

A preliminary hydrogeological investigation was carried out at the Waite Amulet tailings in 1985 (Siwik, 1986). Figure 1 shows the location of the Waite Amulet tailings. The work was initiated by the Centre de Recherche Noranda as part of a larger project to undertake a five year hydrogeochemical investigation of the Waite Amulet tailings area near Noranda, Quebec. The study is part of a joint industry/CANMET program known as the Reactive Acid Tailings Program (RATS).

A hydrogeological investigation was initiated in 1985 to: 1) define the extent and variation of tailings deposition and the type of geological material underlying the tailings; and 2) install a piezometer network to assess the hydrogeological and geochemical conditions within and below the tailings.

During 1985 various geophysical methods were employed, consisting of seismic, electromagnetic conductivity, and electrical resistivity, to assess both the tailings characteristics and the applicability of the techniques employed. Hydrogeochemical methods were employed consisting of: installation of piezometer nests to determine groundwater flow patterns and porewater chemistry in and below the tailings; and, obtaining solid core samples to characterize the physical chemical and mineralogical parameters and determine iron oxidizing and sulphate reducing bacterial counts.



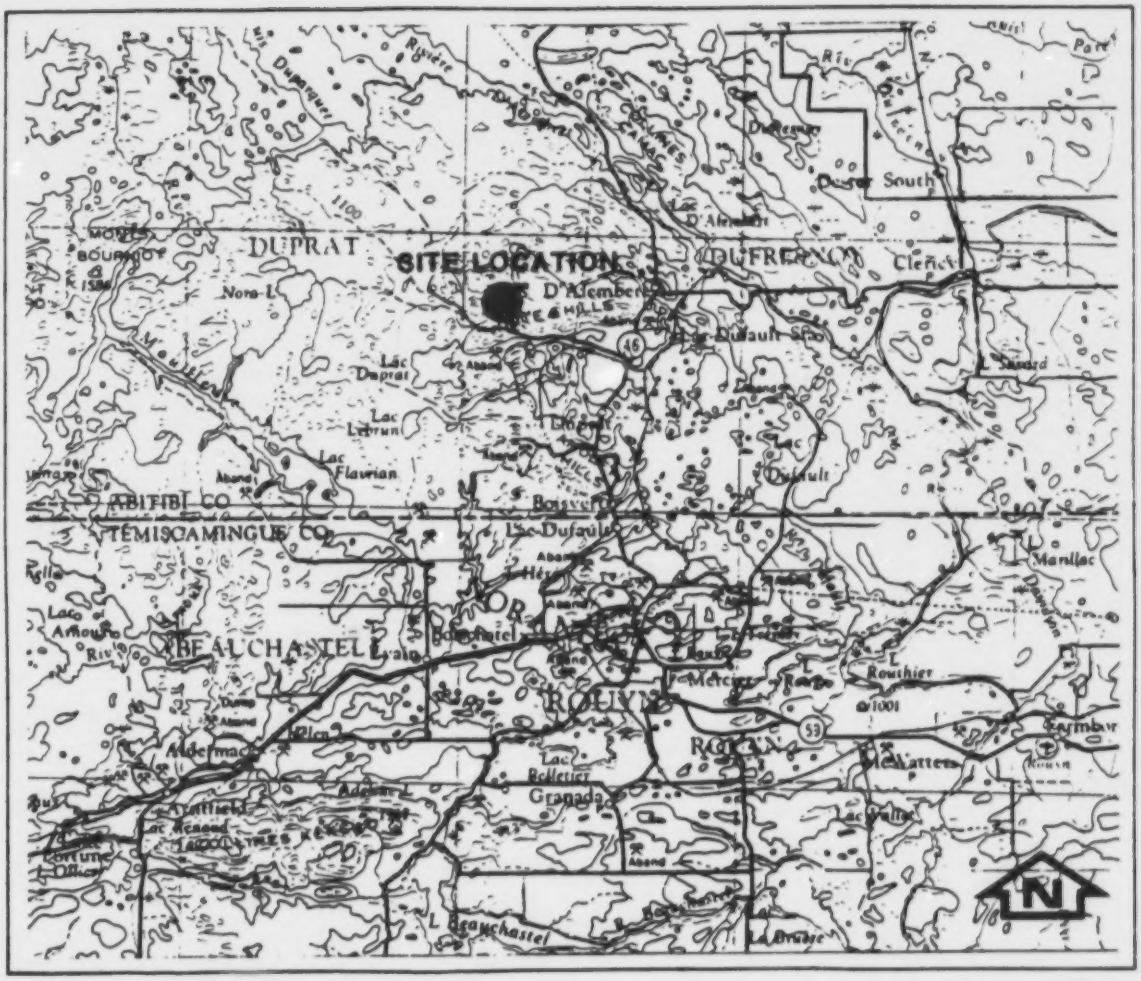


FIGURE 1 SITE LOCATION

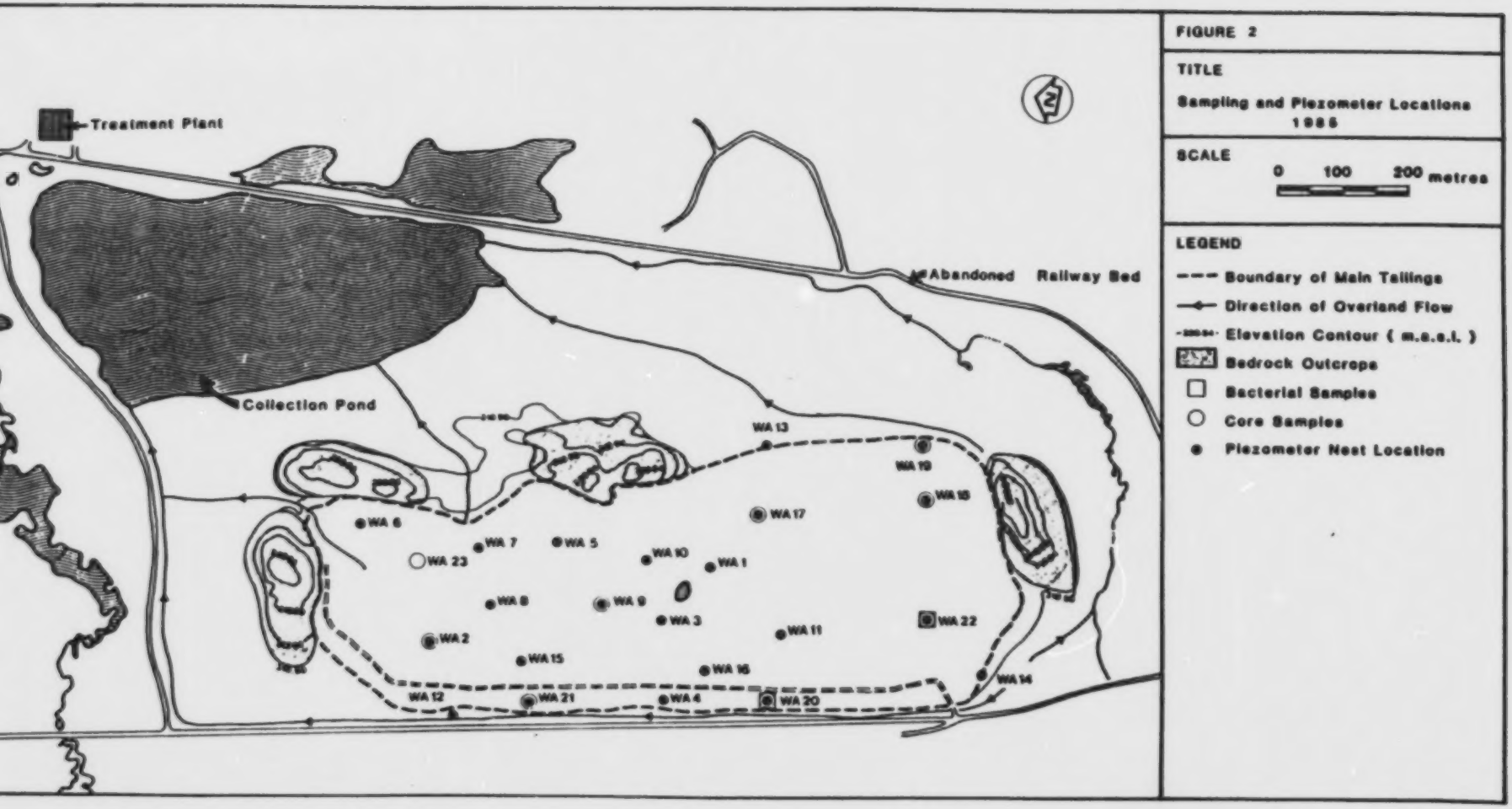


FIGURE 2

TITLE

Sampling and Piezometer Locations
1985

SCALE

0 100 200 metres

LEGEND

- Boundary of Main Tailings
- Direction of Overland Flow
- Elevation Contour (m.a.s.l.)
- Bedrock Outcrops
- Bacterial Samples
- Core Samples
- Piezometer Nest Location

A total of 55 piezometers were installed at 23 locations (Figure 2). Continuous solid cores were collected at nine locations, six on top of the main tailings and three along the tailings dam. Preliminary pH and electrical conductance measurements were obtained at each piezometer location and ten locations were selected for detailed chemical analyses. Two of the nine cores were selected for detailed biological investigations.

Results of 1985 study program are presented in a report by Richard Siwik, July, 1986 entitled "Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Quebec - 1985 Program". Based on the data collected and results of the 1985 program, several recommendations were made with respect to further data collection to better define site conditions.

1.2 Objective of the 1986 Program

The objectives of the 1986 Field Program were outlined in the 1985 report by Siwik. The objectives and specific sections of the request for proposal (RFP) as they pertain to the work outlined in this report are described below.

1) <u>Finalize Site Hydrogeology</u>

A downward hydraulic gradient in the northern section of the tailings indicates a possible hydraulic connection between the tailings and underlying rock. The groundwater flow direction and movement along the seepage face will be further refined.

2) Evaluate Geochemistry of the Unsaturated Zone and Dam Face

An investigation of the biohydrogeochemical processes and controlling mechanisms will be undertaken via:

- analysis of core samples and porewater samples in the unsaturated zone
- monitoring of the oxygen profile
- monitoring of metal loadings and flow through and out of the tailings
- monitoring rainfall and evaporation.

Only a portion of the first method of investigation was undertaken by Terraqua Investigations Ltd. (Terraqua).

The field investigation performed by Terraqua as per the RFP were as follows:

1) Assess the Hydraulic Connection of the Tailings with the Underlying Clay and Host Rock

This involved coring and installation of piezometers at several locations as outlined by Noranda. It also involved installation of piezometers at selected locations in the underlying clay.

2) Finalize Site Hydrogeology

Approximately 20 more piezometers were installed at selected locations, primarily along the western half of the tailings dam, to supplement the monitoring network installed during the 1985 field investigation.

3) Evaluate the Geochemistry of the Unsaturated Zone and Dam Face

The small portion of this investigation was performed by Terraqua and consisted of installation of several suction lysimeters along the dam face and in the unsaturated zone in the southern part of the tailings. The remainder of the unsaturated zone work was performed by the University of Waterloo, under contract to Noranda.

2.0 METHODS OF INVESTIGATION

2.1 Drilling and Solid Sampling

A CME 750 drill rig was utilized for all drilling and sampling during the 1986 drilling program. The drill rig was utilized primarily for bedrock coring and the installation of piezometers. Soil samples were collected primarily for stratigraphic interpretation (i.e. tailings/native material interface) as solid cores were collected during the 1985 Field Program.

Soil samples which were collected during 1986 Field Program consisted of split spoon samples at selected locations to better define the contact of the tailings/peat-clay interface.

Rock coring was performed at two locations to examine the hydrogeological characteristics of the underlying rock and to allow for installation of piezometers in the bedrock. Rock coring was done by first hollow stem augering to the bedrock interface and utilizing the augers as a casing. A small amount of bentonite was placed in the bottom of the borehole to minimize water losses during coring.

Coring was accomplished by diamond drilling and using an NV3 core barrel to obtain 5 cm (2 inch) OD continuous rock core from a 7.5 cm (3 inch) ID core hole. Water from the treatment plant was used during drilling. Electrical conductivity and pH were measured on several occasions prior to the drilling water entering the borehole.

2.2 Piezometer Installation

Two types of piezometers were installed during this phase of work. Piezometers installed in the tailings were a modified casagrande drive-point piezometer, as described in the 1986 Report by Siwik, summarizing the 1985 Field Program. These piezometers were installed utilizing the drill rig, at locations where manual installation techniques utilized during the 1985 Field Program were not adequate. Boreholes were augered to a depth of 0.5 - 1.0 metres above the desired location of the piezometer to be installed. The piezometer was hand driven the remaining distance to allow installation in tailings with a minimum of disturbance around the piezometer tip. The augers were then pulled back and a bentonite seal placed in the borehole annulus to prevent the possibility of porewater or oxygen gas from migrating down the outside of the piezometer pipe.

Piezometers installed in the underlying clay and bedrock were conventional well screens consisting of machine slotted (No. 10 slot) schedule 40 PVC pipe. They ranged in length from 1.2 to 1.5 metres. These piezometers were installed inside the hollow stem augers and a silica sandpack placed around the screened section. The borehole was then filled with bentonite to the clay interface to prevent a connection along the borehole annulus between the tailings material above and the piezometer in the clay or bedrock below.

2.3 Suction Lysimeter Installation

Suction lysimeters were installed at two locations, one location in the central portion of the tailings area and another location along the tailings dam. Suction lysimeters were installed as shown in Figure 3.

A borehole was drilled to the desired depth of installation and the augers were removed. Because the tailings were unsaturated and relatively coarse the borehole stayed open. Bentonite was placed in the bottom of the borehole and a small amount of fine sand placed above the bentonite. The lysimeter was then placed in the borehole and fine sand packed around the porous ceramic cup, taking care to keep the lysimeter centered in the borehole. Sand was then placed to above the sampler and a bentonite seal placed above this. A small amount of water was used to saturate the bentonite to allow it to expand. The remainder of the borehole was backfilled with native material, which was tamped continuously as the borehole was backfilled.

2.4 Water Level Monitoring

Water levels were monitored upon installation of each piezometer to monitor the rate of recovery and determine when water levels have stabilized. A complete set of water levels were obtained for all piezometers installed to date. Water levels were measured, using a coaxial cable electric probe, as depth below the top of the uncapped piezometer pipe.

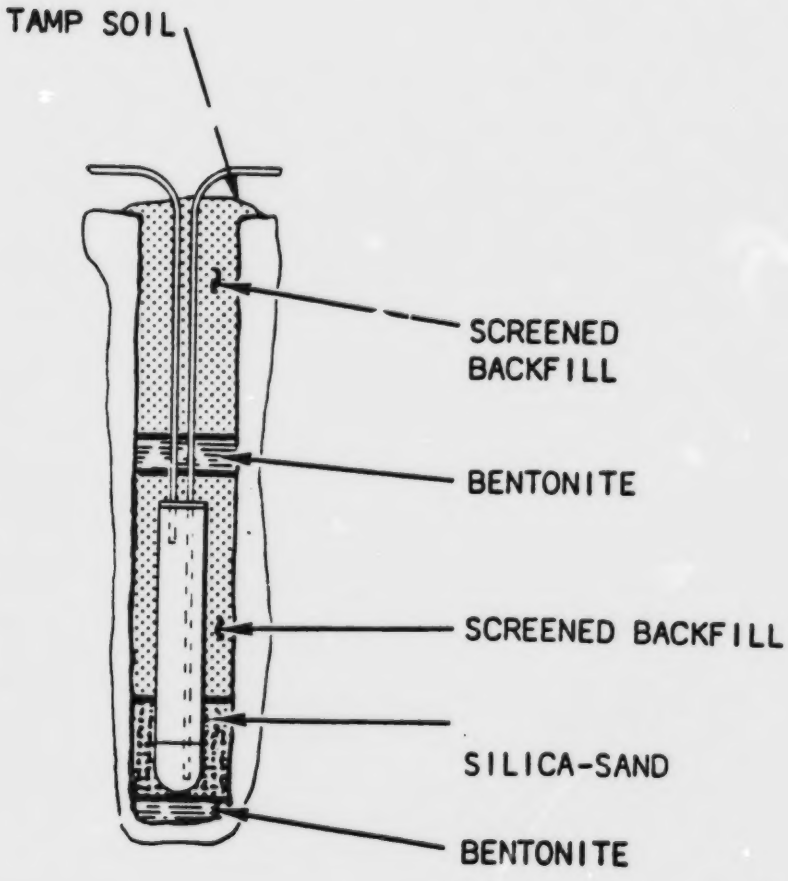


Figure 3 Suction Lysimeter Installation

Monitoring the water level recoveries after installation of the piezometers, was done to allow an estimation of hydraulic conductivity to be made for the zone immediately adjacent to the piezometer tip and to determine when the water levels had stabilized.

3.0 RESULTS AND DISCUSSION

3.1 Drilling and Solid Sampling

Drilling was carried out at eight locations as shown in Figure 4. Four locations were previously drilled and drilling during the 1986 program at these sites was done to install more piezometers and obtain bedrock core at two locations, WA2 and WA9. The two locations for bedrock coring were selected for the following reasons. One site, WA2, has a strong vertically downward hydraulic gradient and a thin clay layer, indicating a possible hydraulic connection between the tailings and the bedrock. The other site, WA9, also showed a moderately strong downward gradient and a thin clay layer but the bedrock elevation appeared to be anomalously high at this location.

At five of the other six drilling locations boreholes were augered to the tailings/clay interface and two of the six locations boreholes were augered to bedrock. Most boreholes were concentrated in the northern portion of the site.

Figure 5 shows updated elevations of the clay surface underlying the tailings. The clay surface in the northern portion of the site generally slopes to the west. The relief of the clay slope is relatively gentle. The slope of the underlying bedrock in this portion of the site is also to the east, however the relief is much greater.

Results of the rock coring at WA2 and WA9 indicate bedrock to be an acidic volcanic type rock (granodiorite?) that is moderately

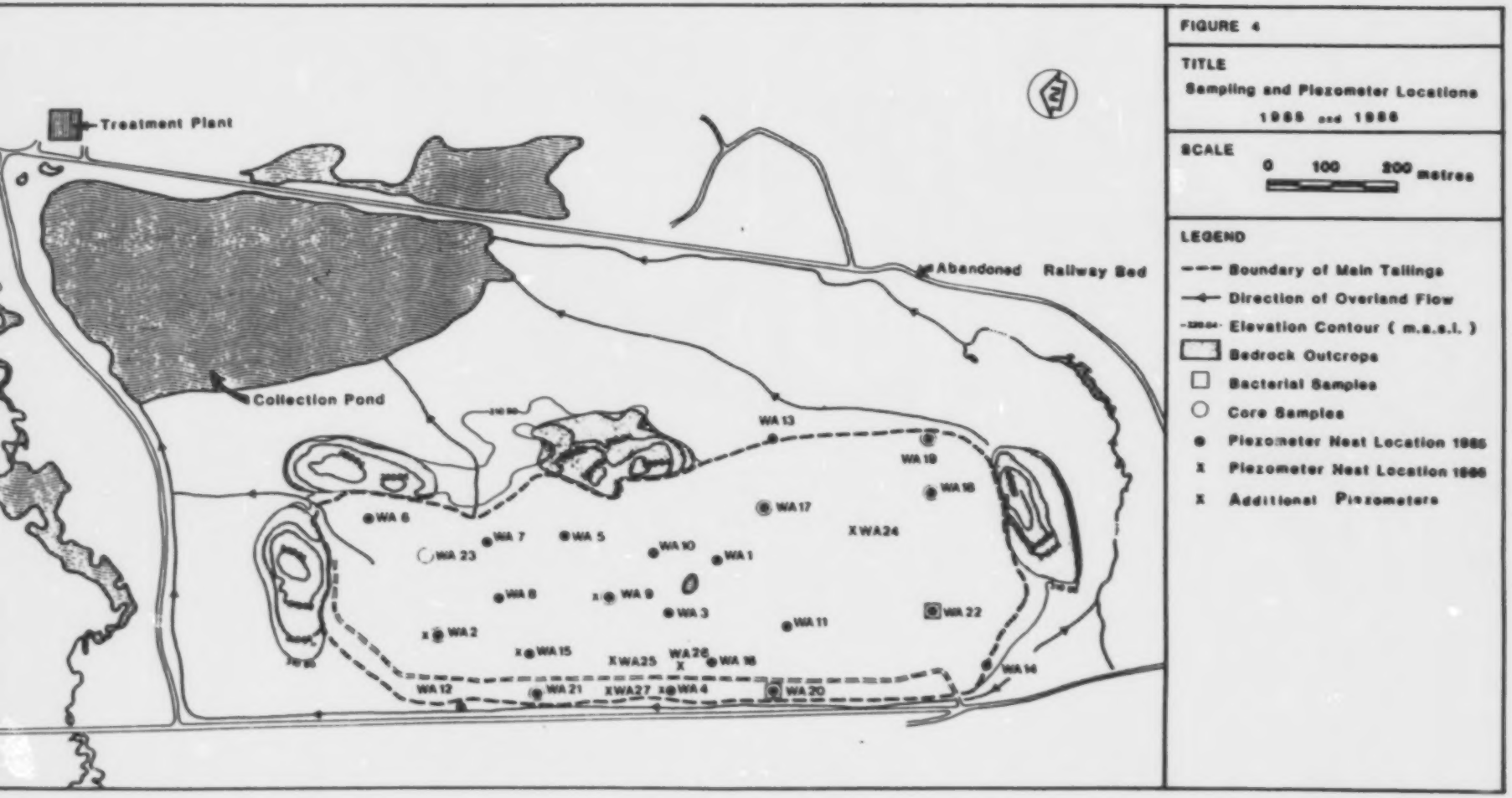


FIGURE 4

TITLE
Sampling and Piezometer Locations
1985 and 1986

SCALE
0 100 200 metres

LEGEND
- Boundary of Main Tailings
- Direction of Overland Flow
- Elevation Contour (m.a.s.l.)
- Bedrock Outcrops
- Bacterial Samples
- Core Samples
- Piezometer Nest Location 1985
- Piezometer Nest Location 1986
- Additional Piezometers

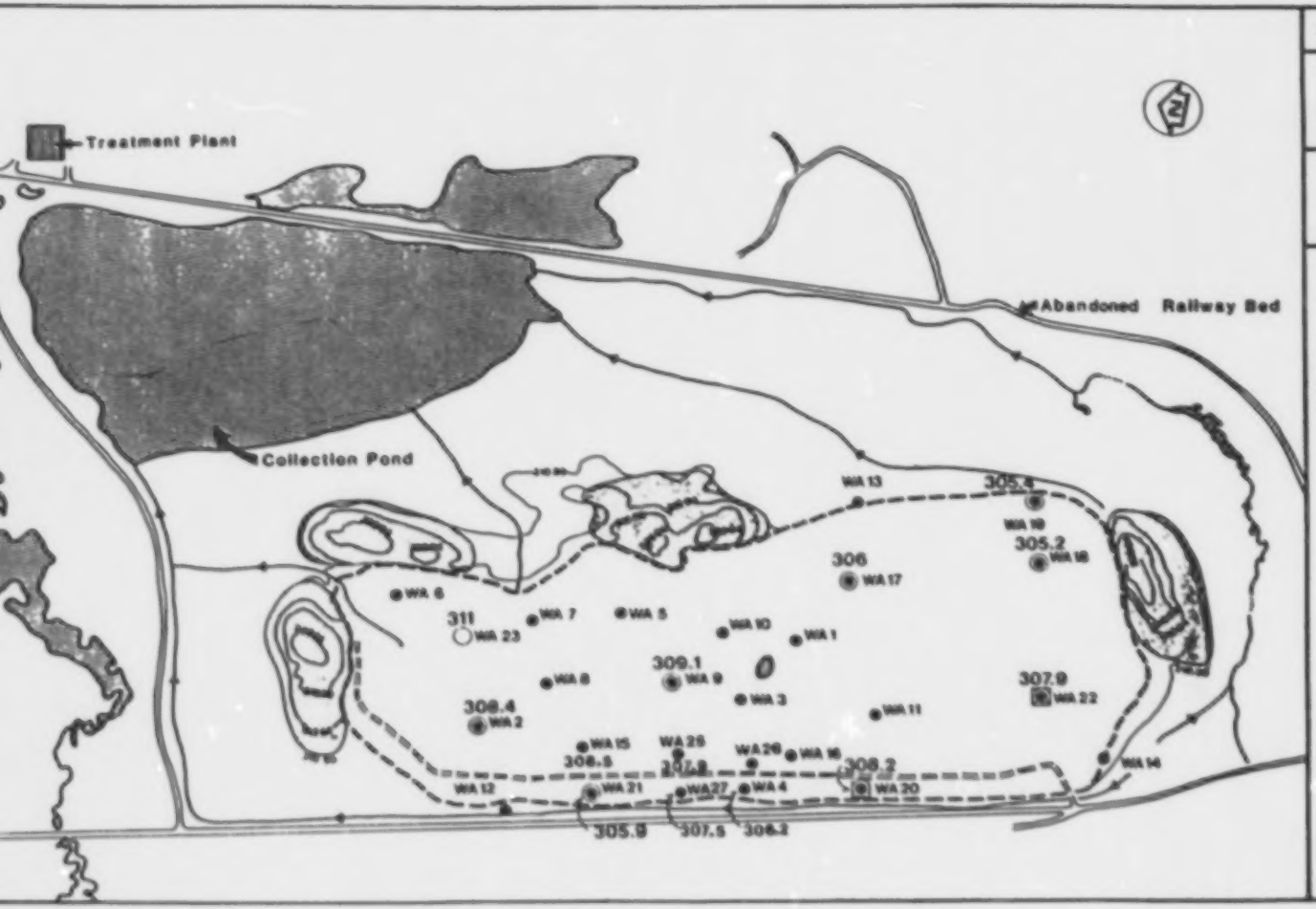


FIGURE 5

TITLE

Elevation of Clay Surface

SCALE

0 100 200 metres

LEGEND

- Boundary of Main Tailings
- Direction of Overland Flow
- Elevation Contour (m.a.s.l.)
- Bedrock Outcrops
- Bacterial Samples
- Core Samples
- Piezometer Nest Location
- 306 Clay Surface Elevation metres

fractured. A detailed description of the rock core is presented in Table A2 found in Appendix A. A 3 metre core was obtained from each site. The bedrock at WA9 was less fractured than at WA2. Most fractures at WA9 were at a 45 degree or 60 degree angle, were relatively tight and chlorite was present on most of the fracture surfaces. There were no noticeable high hydraulic conductivity zones at WA9.

Rock core obtained at WA2 had a slightly darker more crystalline matrix. Fracture orientations were generally at 45 degrees however several large vertical fractures were present which appeared to be relatively high hydraulic conductivity zones.

3.2 Groundwater Flow System

The scope of work for the portion of 1986 program carried out by Terraqua did not involve a further assessment or interpretation of the groundwater flow system but was essentially the installation of more piezometers to supplement the 1985 program. The piezometers were not level surveyed to the existing network. Water levels were collected during the short duration of the field program to obtain at least one set of stabilized levels where possible. Water levels collected for the piezometer installed in 1985 are presented in Table A1, found in Appendix B. Water levels recorded during the installation of piezometers for the 1986 field program are presented in Table A2, found in Appendix B.

A general discussion of the groundwater flow system was presented in the January 1986 report by Terraqua (Siwik, July 1986) and will

not be reiterated here. Some general comments can be made based on data collected during the 1986 drilling program. A more detailed interpretation of the flow system cannot be made until the piezometers are level surveyed into the existing network and all the water levels have been allowed to stabilize. Because the test drilling and piezometer installation for 1986 concentrated on the northwest portion of the tailings, this is the only area where a further evaluation of the flow system can be made.

Preliminary results indicate that the water level in the bedrock at WA9 is higher than in the clay zone immediately above resulting in a vertically upward hydraulic gradient. This would mean that at this location the tailings porewater could not migrate into the bedrock. Drilling indicated that the bedrock core at this location is fractured but relatively tight compared to WA2. Sampling of the clay in the 1985 drilling program indicated that the lower portion of the clay unit was quite brittle and water was encountered (i.e. water quickly rose up inside the augers) when drilling into the lower portion of the clay.

Figure 6 shows cross-section A-A' taken from the July 1986 report by Siwik. As can be seen from the cross-section, the clay appears to thicken and the bedrock elevation drops off rapidly to the south. This bedrock high would appear to correspond to the bedrock outcrop to the east. The bedrock is at greater depth at WA27 immediately west of WA25 and WA9 indicating a drop in the bedrock surface to the west. The clay also thickens at this location. WA15 also showed a lower bedrock elevation than both

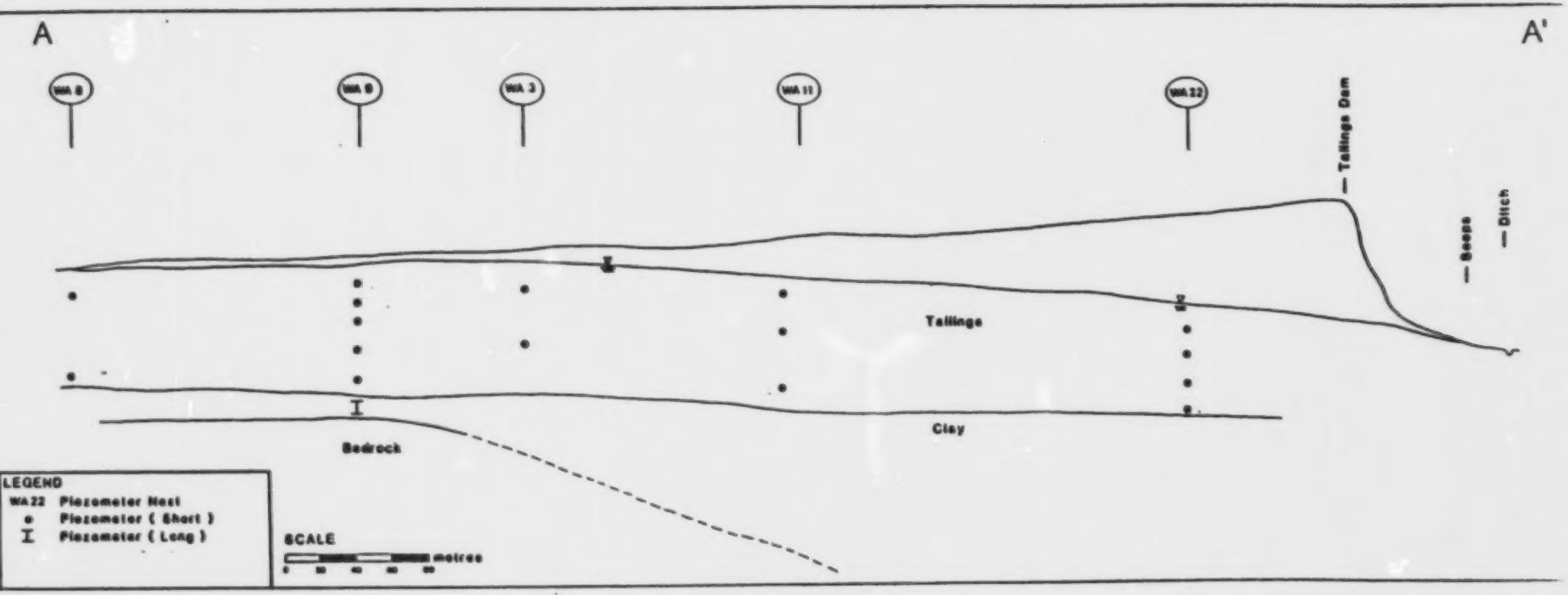


Figure 6 Cross-Section A-A'

WA2 and WA25 indicating a bedrock trough between these two locations.

WA2 showed a downward vertical gradient into the bedrock. The bedrock was highly fractured in this area and showed considerable vertical fracturing. It would appear that tailings porewater is being recharged into the bedrock at this location. It would also appear that there is only a small percentage of the tailings area where the bedrock is being recharged by tailings porewater. This occurs where areas of thin clay and fractured bedrock underly the tailings. These areas are limited to the north central portion of the tailings area where the hydraulic conductivity of the tailings is relatively low. The clay appears to be thick enough along the northwest dam face to prevent any downward migration of tailing porewater to the bedrock.

A rough estimate of the flux into the bedrock can be made using several assumptions, and the Darcy Equation $q = KIA$ where; q is the groundwater flux, $[L^3/T]$; K is the hydraulic conductivity, [L/T]; I is the hydraulic gradient, [L/L]; and A is the area of the bedrock through which the tailings porewater is moving $[L^2]$. The following assumptions were made to provide an estimate of flux into the bedrock: K is estimated to be 2×10^{-6} cm/sec, I is estimated to be 0.3, and A is estimated to be about 2.2 ha or 5.5% of the entire tailings area. The flux is equivalent to about 8 Lpm. Based on estimates of flux from the 1985 study this is equivalent to about 3.5% of the estimated flux out of the tailings. These values are only rough estimates but do give an

indication of the quantities and percentage of porewater migration into the bedrock.

4.0 CONCLUSIONS AND RECOMMENDATIONS

1) Routine monitoring of water levels should be performed at least once a month and increased in frequency during the spring runoff to examine the hydraulic connection of the various geological units and various areas of tailings to the spring recharge event.

2) Hydraulic conductivity testing should be performed on the piezometers located in the clay and bedrock to further delineate the hydrogeological regime.

3) Piezometers installed in the clay and bedrock should be flushed out as much as possible prior to geochemical sampling.

4) Suction lysimeters should be assessed as to there usefulness in this type of setting as well as the adequacy of their installation procedure. They should be sampled in the field prior to additional installations.

APPENDIX A

BOREHOLE LOGS

BOREHOLE NO. WA2

PROJECT Waite Amulet Tailings
CLIENT Noranda
BOREHOLE TYPE H.S. Auger

GEOLOGIST RJB
DATE November 1, 1988
ELEVATION 314.7 m

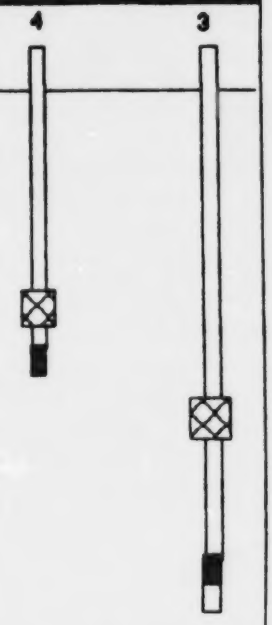
DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
				5
0				
	TAILINGS, black, fine – grained cohesive			
1				
2				
			AS	
3				
4				
5				
			AS	
6				
	CLAYEY SANDY SILT			
7				
	BEDROCK, granitic, highly fractured (see Table A2 for details)		core	
8			core	
			core	
9			core	
			core	
10			core	
	Borehole terminated			
11				
12				
13				

BOREHOLE NO. WA4

PROJECT Waite Amulet Tailings
CLIENT Noranda
BOREHOLE TYPE H.S. Auger

GEOLOGIST RJB
DATE November 3, 1988
ELEVATION 312.5 ± m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0	TAILINGS brown, medium to coarse grained		AS	4 3
1				
2				
3			AS	
4				
5			AS	
6			SS	
7	PEAT/CLAY contact Borehole terminated			
8				
9				
10				
11				
12				
13				



BOREHOLE NO. WA9

PROJECT Waite Amulet Tailings **GEOLOGIST** RJB

CLIENT Noranda **DATE** November 1, 1986

BOREHOLE TYPE H.S. Auger **ELEVATION** 315.9 m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
				7
0				
	TAILINGS, black, fine – grained cohesive			
1				
2				
			AS	
3				
4				
5				
			AS	
6				
7				
	CLAY, gray, dense			
8				
	BEDROCK, granitic, fractured (see table A2 for details)		core	
9			core	
			core	
10			core	
	Borehole terminated			
11				
12				
13				

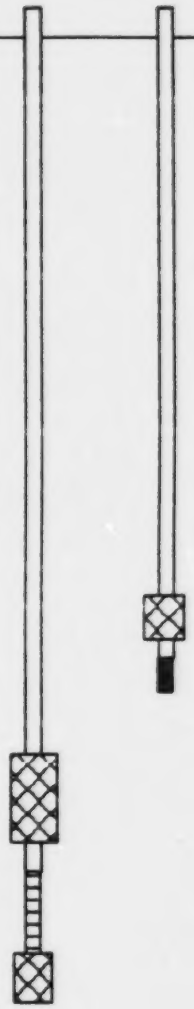
BOREHOLE NO. WA16

PROJECT Waite Amulet Tailings **GEOLOGIST** RJB

CLIENT Noranda **DATE** November 2, 1986

BOREHOLE TYPE H.S. Auger **ELEVATION** 315.9 m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0	TAILINGS, dark, fine – grained			3 4
1				
2				
3	– saturated			
4				
5				
6				
7				
8	CLAY, gray dense			
9				
10				
11	Borehole terminated refusal			
12	Bedrock			



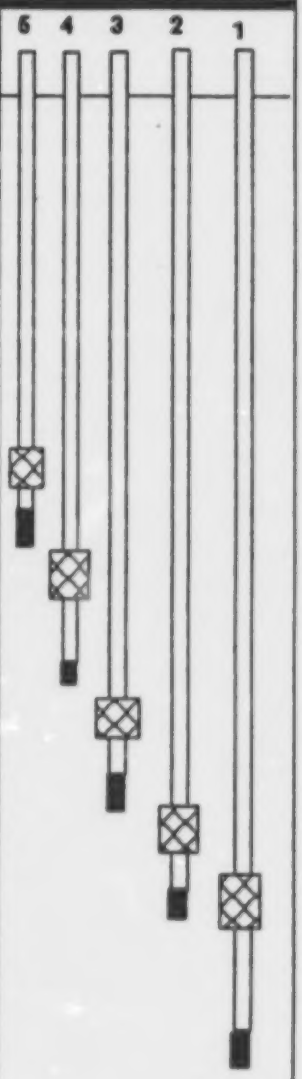
BOREHOLE NO. WA24

PROJECT Waite Amulet Tailings GEOLOGIST RJB

CLIENT Noranda DATE October 31, 1986

BOREHOLE TYPE H.S. Auger ELEVATION

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0	TAILINGS, black, fine – grained		AS	5 4 3 2 1
1				
2				
3	– saturated		AS	
4				
5				
6			AS	
7				
8			AS	
9				
10			AS	
11	Borehole terminated			
12				

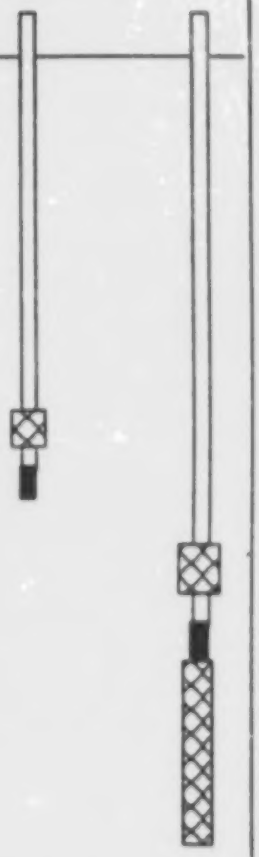


BOREHOLE NO. WA25

PROJECT Waite Amulet Tailings
CLIENT Noranda
BOREHOLE TYPE H.S. Auger

GEOLOGIST RJB
DATE November 2, 1988
ELEVATION 318.5 ± m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0				2 1
1	TAILINGS, black, fine-grained, high metal content at depth		AS	
2				
3			AS	
4				
5	- saturated		AS	
6				
7				
8				
9	CLAY, dense, gray		AS	
10	Borehole terminated - Bedrock			
11				
12				
13				

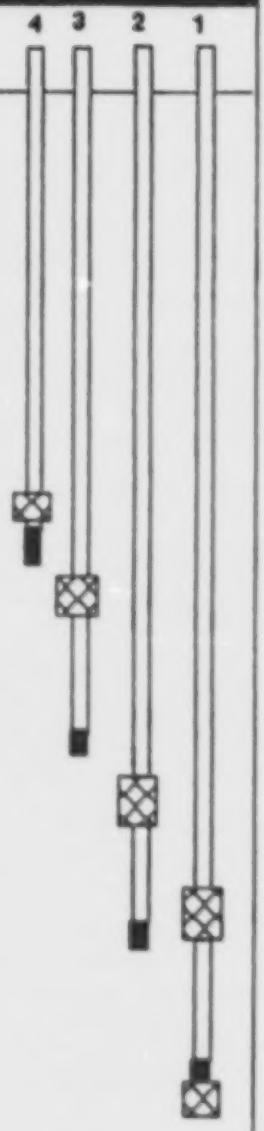


BOREHOLE NO. WA28

PROJECT Waite Amulet Tailings
CLIENT Noranda
BOREHOLE TYPE H.S. Auger

GEOLOGIST RJB
DATE November 2/3, 1986
ELEVATION 318.0 ± m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0	TAILINGS, black, silty sand			4 3 2 1
1				
2			AS	
3			AS	
4				
5	– fine – grained, saturated 4.5 – 6.0m		AS	
6				
7	– softer			
8			AS	
9				
10				
11	– high metal content		SS	
12	PEAT/CLAY contact		SS	
13	Borehole terminated			



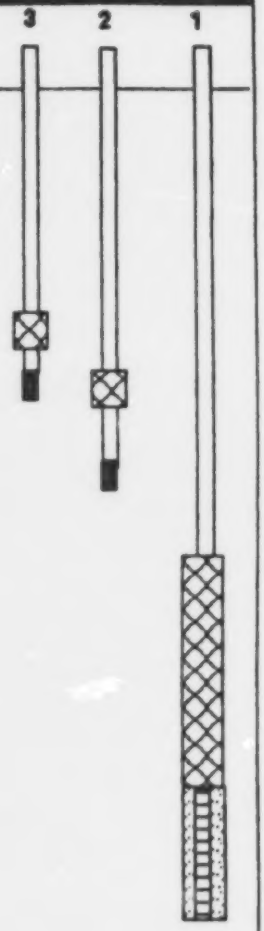
BOREHOLE NO. WA27

PROJECT Waite Amulet Tailings **GEOLOGIST** RJB

CLIENT Noranda **DATE** November 3, 1986

BOREHOLE TYPE H.S. Auger **ELEVATION** 312.5 + m

DEPTH metres	DESCRIPTION	SAMPLES NO	SAMPLES TYPE	GROUND WATER MONITORS
0				3 2 1
1	TAILINGS, brown, coarse, uncohesive		AS	
2				
3	– saturated		AS	
4				
5				
6	CLAY, gray, dense, pliable		SS	
7				
8				
9				
	Borehole terminated			
10	Bedrock			
11				
12				
13				



PIEZOMETER	SCREENED INTERVAL (metres b.g.s.)	BENTONITE SEAL (metres b.g.s.)	GEOLOGIC UNIT
WA 2-5	7.8 - 9.0	6.7 - 7.6	
		9.0 - 10.4	BEDROCK
WA 4-3	5.3 - 5.45	3.4 - 3.7	TAILINGS
WA 4-4	3.0 - 3.15	2.4 - 2.7	TAILINGS
WA 9-7	9.1 - 10.4	7.8 - 8.9	BEDROCK
WA15-3	9.5 - 10.7	8.2 - 9.2	TAILINGS
		10.7 - 11.0	CLAY
WA15-4	7.6 - 7.75	7.0 - 7.5	TAILINGS
WA24-1	11.0 - 11.15	8.2 - 8.5	TAILINGS
WA24-2	9.15 - 9.30	8.0 - 8.3	TAILINGS
WA24-3	7.8 - 7.95	7.0 - 7.3	TAILINGS
WA24-4	6.50 - 6.65	5.2 - 5.5	TAILINGS
WA24-5	4.90 - 5.05	4.0 - 4.3	TAILINGS
WA25-1	6.40 - 6.55	5.5 - 6.2	TAILINGS
		6.7 - 8.8	TAILINGS
WA25-2	4.90 - 5.05	4.3 - 4.6	TAILINGS
WA26-1	11.10 - 11.25	9.1 - 9.4	TAILINGS
		11.3 - 11.5	TAILINGS
WA26-2	9.45 - 9.60	7.9 - 8.2	TAILINGS
WA26-3	7.30 - 7.45	5.5 - 5.8	TAILINGS
WA26-4	5.20 - 5.35	4.8 - 5.0	TAILINGS
WA27-1	8.2 - 9.4	5.3 - 8.0	CLAY
WA27-2	4.60 - 4.75	3.2 - 3.5	TAILINGS
WA27-3	3.20 - 3.35	2.6 - 2.9	TAILINGS

Table A1 - Piezometer Installation Details

WA9

Cored : 7.9 - 10.36 m

RQD : 0.77

Fractures : 8.53 m, 8.91 m, 9.07 m, 9.22 m, 9.75 m, 9.33 m, 10.28 m,

Fracture Orientation : Most Fractures were at 45 degree or 60 degree angle to horizontal, no vertical fracture present

Fracture Description : tight, chlorite on most faces, some cementation on fractures

WA2

Cored : 7.3 - 10.36 m

RQD : 0.60

Fractures : Vertical, 7.92 - 8.12 m, 8.38 - 8.74 m, 10.36 - 10.46; Horizontal: 8.12 m, 8.74 m; 45 degree angle; 9.9 m, 10.05 m,

Fracture Description : most fractures not tight (high k), little staining or cementing

Table A2 - Description of Rock Core

Location	Lysimeter No.	Depth of Porous Cup (metres)	Depth of Sandpack (metres)	Depth of Bentonite Seal (metres)
WA21	L1	2.05	1.4 - 2.1	1.1 - 1.4
WA21	L2	1.12	0.9 - 1.2	0.5 - 0.9
WA24	L1	2.69	2.1 - 2.8	1.7 - 2.1
WA24	L2	1.98	1.2 - 2.1	0.9 - 1.2

Table A3 - Suction Lysimeter Installation Details

APPENDIX B

WATER LEVEL DATA

Piezometer	Depth to Water (below top of pipe)	Water Level	Date (1986)	Piezometer	Depth to Water	Water Level	Date (1986)
WA1-1	2.66	315.07	Nov.1	WA12-1	-		
WA1-2	1.08	315.94	Nov.1	WA13-1	1.27	310.00	Nov.3
WA2-1	3.56	312.9	Nov.1	WA14-1	1.94	312.12	Nov.1
WA2-2	1.29	314.11	Nov.1	WA15-1	5.64	311.52	Nov.1
WA2-3	2.14	313.46	Nov.1	WA15-2	dry		Nov.1
WA2-4	2.69	312.96	Nov.1	WA16-1	7.46	311.91	Nov.3
WA3-1	2.02	315.23	Nov.1	WA17-1	3.91	313.92	Nov.1
WA3-2	1.56	315.69	Nov.1	WA17-2	3.76	314.06	Nov.1
WA4-1	-			WA17-3	3.72	314.08	Nov.1
WA4-2	-			WA17-4	3.75	314.09	Nov.1
WA5-1	1.61	315.49	Nov.1	WA17-5	3.81	313.97	Nov.1
WA5-2	1.57	315.54	Nov.1	WA17-6	9.38	308.59	Nov.1
WA6-1	1.89	314.34	Nov.3	WA18-1	9.26	310.01	Nov.3
WA7-1	1.35	314.83	Nov.1	WA18-2	6.61	312.59	Nov.3
WA8-1	3.23	313.74	Nov.1	WA18-3	6.60	312.58	Nov.3
WA8-2	1.60	315.27	Nov.1	WA18-4	6.62	312.67	Nov.3
WA9-1	3.10	314.03	Nov.1	WA18-5	6.58	312.69	Nov.3
WA9-2	1.37	315.75	Nov.1	WA19-1	2.80	309.60	Nov.3
WA9-3	2.15	314.98	Nov.1	WA19-2	2.99	309.57	Nov.3
WA9-4	1.68	315.41	Nov.1	WA20-1	3.37	311.18	Nov.3
WA9-5	1.49	315.64	Nov.1	WA20-2	3.40	311.25	Nov.3
WA9-6	3.54	313.74	Nov.1	WA21-1	3.24	309.83	Nov.3
WA10-1	1.63	315.49	Nov.1	WA21-2	3.03	309.81	Nov.3
WA10-2	1.43	315.73	Nov.1	WA22-1	6.37	313.43	Nov.2
WA11-1	4.19	314.12	Nov.1	WA22-2	6.36	313.43	Nov.2
WA11-2	3.73	314.59	Nov.1	WA22-3	6.31	313.39	Nov.2
WA11-3	3.32	314.96	Nov.1	WA22-4	6.39	313.41	Nov.2

Table B1 Water Levels for Piezometers Installed During 1985

WA1-1	317.73	WA12-1	311.33
WA1-2	317.02	WA13-1	311.27
WA2-1	315.65	WA14-1	314.06
WA2-2	315.49	WA15-1	317.16
WA2-3	315.60	WA15-2	317.14
WA2-4	315.65	WA16-1	319.37
WA3-1	317.25	WA17-1	317.83
WA3-2	317.25	WA17-2	317.82
WA4-1	310.75	WA17-3	317.80
WA4-2	312.24	WA17-4	317.84
WA5-1	317.10	WA17-5	317.78
WA5-2	317.11	WA17-6	317.97
WA6-1	316.23	WA18-1	319.27
WA7-1	316.18	WA18-2	319.20
WA8-1	316.97	WA18-3	319.18
WA8-2	316.87	WA18-4	319.29
WA9-1	317.13	WA18-5	319.27
WA9-2	317.12	WA19-1	312.40
WA9-3	317.13	WA19-2	312.56
WA9-4	317.09	WA20-1	314.55
WA9-5	317.13	WA20-2	314.65
WA9-6	317.28	WA21-1	313.07
WA10-1	317.12	WA21-2	312.84
WA10-2	317.16	WA22-1	319.80
WA11-1	318.31	WA22-2	319.79
WA11-2	318.32	WA22-3	319.70
WA11-3	318.28	WA22-4	319.80

Table B2 Elevation of the Top of the Uncapped Piezometers

Piezometer WA2-5
Installation:
Nov. 1 - 8:30 pm
Total Casing Length:
10.0 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	2:30pm	4.05			
Nov. 2	5:00pm	4.08			
Nov. 3	9:40am	4.06			

Piezometer WA4-3
Installation:
Nov. 3 - 11:40
Total Casing Length:
6.6 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	11:46am	3.76	Nov. 3	12:00pm	2.99
Nov. 3	11:48am	3.67	Nov. 3	12:24pm	2.45
Nov. 3	11:52am	3.38	Nov. 3	2:25	2.03

Piezometer WA4-4
Installation:
Nov. 3 - 12:00
Total Casing Length:
4.20 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	12:07	1.86			
Nov. 3	12:14	1.84			
Nov. 3	2.25	1.81			

Piezometer WA9-7
Installation:
Nov. 1 - 4:00 pm
Total Casing Length:
11.8 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	9:00am	2.97			
Nov. 2	2:30pm	2.93			
Nov. 3	9:50am	2.92			

Piezometer WA15-3
Installation:
Nov. 2 - 12:50 pm
Total Casing Length:
12.3 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	12:57pm	5.17	Nov. 3	9:50am	4.99
Nov. 2	2:03	5.05			
Nov. 2	3:50	5.09			

Piezometer WA15-4
Installation:
Nov. 2 - 1:40 pm
Total Casing Length:
9.0 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	1:46pm	8.34	Nov. 3	9:50am	6.73
Nov. 2	3:20pm	8.15			
Nov. 2	4:50pm	7.98			

Table B3 Water Level Measurements, Piezometers Installed in 1986

Piezometer WA24-1
Installation:
Oct. 31 - 6:00 pm
Total Casing Length:
11.7 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Oct.31	6:10pm	11.66	Nov. 1	5:20	5.73
Oct.31	7:30pm	10.90	Nov. 2	8:30	5.14
Nov. 1	8:24am	6.73	Nov. 3	12:30	4.81

Piezometer WA24-2
Installation:
Oct. 31 - 7:00 pm
Total Casing Length:
10.3 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Oct.31	7:05pm	9.39	Nov. 1	5:21pm	4.66
Oct.31	8:05pm	8.15	Nov. 2	8:30am	4.56
Nov. 1	8:25am	4.83	Nov. 3	12:30pm	4.46

Piezometer WA24-3
Installation:
Oct. 31 - 8:00 pm
Total Casing Length:
8.8 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Oct.31	8:10pm	8.60	Nov. 2	8:30am	4.08
Nov. 1	8:30am	4.11	Nov. 3	12:30	4.01
Nov. 1	5:22	4.19			

Piezometer WA24-4
Installation:
Nov. 1 - 9:20 am
Total Casing Length:
7.5 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 1	9:25am	7.01	Nov. 1	5:23pm	5.58
Nov. 1	10:18am	6.80	Nov. 2	8:30am	4.41
Nov. 1	12:00pm	6.43	Nov. 3	12:30pm	3.97

Piezometer WA24-5
Installation:
Nov. 1 - 10:05 am
Total Casing Length:
6.0 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 1	10:10	5.41	Nov. 1	5:24pm	4.24
Nov. 1	11:04	5.18	Nov. 2	8:30am	3.63
Nov. 1	3:08	4.47	Nov. 3	12:30pm	3.53

Piezometer WA25-1
Installation:
Nov. 2 - 3:00 pm
Total Casing Length:
7.6 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	3:46pm	6.78	Nov. 3	9:40am	6.03
Nov. 2	4:03pm	6.55	Nov. 3	2:40pm	6.00
Nov. 2	5.38pm	6.12			

Table B3 Water Level Measurements, Piezometers Installed in 1986

Piezometer WA25-2
Installation:
Nov. 2 - 4:00 pm
Total Casing Length:
6.0 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	4:05pm	5.79	Nov. 3	2:40pm	5.74
Nov. 2	5:39pm	5.78			
Nov. 3	9:00pm	5.76			

Piezometer WA26-1
Installation:
Nov. 2 - 6:15 pm
Total Casing Length:
12.5 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	6:43pm	10.10	Nov. 3	8:50am	6.18
Nov. 2	6:59pm	9.71	Nov. 3	2:35pm	6.03
Nov. 2	7:11pm	9.45			

Piezometer WA26-2
Installation:
Nov. 2 - 7:00 pm
Total Casing Length:
10.6 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 2	7:10pm	10.20			
Nov. 3	9:50pm	6.01			
Nov. 3	2:30pm	5.74			

Piezometer WA26-3
Installation:
Nov. 3 - 9:45 am
Total Casing Length:
8.4 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	10:06am	5.79			
Nov. 3	10:08am	5.77			
Nov. 3	2:30pm	5.72			

Piezometer WA26-4
Installation:
Nov. 3 - 10:20 am
Total Casing Length:
6.4 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	10:31am	5.86			
Nov. 3	10:34am	5.83			
Nov. 3	2:30pm	5.31			

Piezometer WA27-1
Installation:
Nov. 3 - 2:40pm
Total Casing Length:
10.4 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	2:45	4.13			
Nov. 3	3:16	4.11			
Nov. 3	3:48	4.05			

Table B3 Water Level Measurements, Piezometers Installed in 1986

Piezometer WA27-2
Installation:
Nov. 3 - 3:10 pm
Total Casing Length:
5.9 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	3:49	3.48			
Nov. 3	4:24	3.18			

Piezometer WA27-3
Installation:
Nov. 3 - 3:40 pm
Total Casing Length:
4.5 ± m

Depth to Water (metres)					
Date	Time	Depth	Date	Time	Depth
Nov. 3	4:25	2.88			

Table B3 Water Level Measurements, Piezometers Installed in 1986

APPENDIX C

Hydrogeochemical Investigations of the Unsaturated Zone of the Waite Amulet Tailings Site

WRI Award #1142401

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A Final Report

Prepared for

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INTRODUCTION

The oxidation of sulphide minerals within base metal tailings impoundments and the accompanying decline in pore-water pH and increase in concentrations of dissolved constituents is one of the most serious environmental concerns facing the mining industry today. In order to more fully understand this problem, and to design at economical and effective remedial programs a joint industry-government program was initiated. As part of this program a sole-source contract was awarded to Noranda Research to conduct a five-year hydrogeochemical investigation of the abandoned Waite Amulet tailings, near Noranda, Quebec.

Reaserch conducted during the first year of this program included a geophysical survey, installation of a number of piezometer nests into, and through the Waite Amulet tailings, an initial sampling of the saturated-zone tailings pore-water geochemistry, and an assessment of the microbiological community of the tailings. Concurrent with this program researchers from the University of Waterloo conducted an initial sampling of the pore-water geochemistry of the vadose zone. The results of the geochemical investigations indicated that while no low pH pore waters were present in the groundwater-zone pore waters with low pH levels and high concentrations of dissolved constituents were present in the shallow vadose zone.

In order to more fully characterize and understand the pore-water geochemistry of the vadose zone Noranda Research included two tasks (4.3 and 4.4) in the 1986 Waite Amulet drilling program. Task 4.3 included pore-water sampling from 6 locations on the tailings surface and two locations on the tailings dam face, and field analysis of these pore-water samples. Task 4.4 included pore-gas sampling and analysis from various depths of the vadose zone at each of the locations where pore-water samples were collected from the vadose zone.

This report describes the investigations conducted on the vadose zone by researchers from the University of Waterloo, in October 1986. This work was performed to satisfy tasks 4.3 and 4.4 of the request for proposals submitted to the University of Waterloo in August 1986. The first part includes three parts. The first part includes descriptions of field procedures, the second part will provide the results of field measured parameters pH, Eh, specific conductance, ferrous iron concentration, gas phase CO_2 and O_2 concentrations, and the third part will consist of a summary and a brief concluding statement.

FIELD METHODS

A. Pore Water Sampling

In this study pore-water samples were obtained from cores collected from the unsaturated zone of the Waite Amulet tailings. Cores were collected at six sites on top of the tailings and at two sites on the dam face, indicated on Figure 1, as agreed upon by Noranda Research. Pore-water samples were extracted using the immiscible displacement technique described by Smyth (1981), a modification of the technique described by Patterson et al. (1978). Using this technique, cores were collected in 7.62 cm (3 in) aluminum irrigation tubing. Generally cores were collected in 1 or 2 m lengths which were cut into 20 cm lengths. Immediately after cutting, a base plate constructed of Delrin, a commercial plastic, was inserted directly into the base of the core tube. Approximately 2.5 cm of tailings was removed from the top of the core tube and this space was filled with an epoxy plastesizer (Rohm and Hass Paraplex G-62). A Delrin top plate was added immediately above the paraplex and the entire assembly placed in a steel frame and gently squeezed using a small hydraulic jack. The squeezing apparatus is illustrated in Figure 2. This technique has been used successfully at a number of sites, however, inexperienced personnel have a tendency to apply too much pressure to the core too quickly, and as a result the paraplex breaks through along the tubing walls. This is rarely a problem once sufficient expertise is gained by an individual operator. Approximately 40 mL of sample was collected from each 20 cm section of core, this sample was filtered with a 0.45 μm filter, then separated into two aliquots, one acidified with 12N HCl to a pH less than 1.0 for cation analysis and one left unacidified for anion analysis. These samples were submitted to the Environmental Services Laboratory, Noranda

Inc., Noranda, Quebec. As well, subsamples were collected in the field for measurement of pH, eH, specific conductance and for determination of ferrous iron concentrations.

Field measurements of pH were made using an epoxy body Orion Ross pH electrode with a Markson model 95 digital pH meter. The pH meter was calibrated using NBS standards (pH 4, and 7), and a prepared pH 1.68 standard, the calibration was checked on a regular basis. Calibration error throughout the sampling period never exceeded ± 0.02 on the pH 7.00 buffer. Measurements were made immediately following sample extraction and replicate measurements were made on subsequent samples from each core. Measurements of sample Eh were made using an Orion model 96-78 platinum redox electrode. The electrode function was checked throughout the sampling using Zobell's solution, prepared according to Nordstrum (1977). The platinum surface was polished when electrode response appeared to b sluggish. Readings of sample Eh were made immediately after pH measurements o each sample.

The reactive nature of the tailings pore waters leads to dramatic changes i both pH and Eh with exposure to atmospheric O_2, due to the oxidation of Fe^{2+} t Fe^{3+} and the precipitation of Fe^{3+} hydroxides. This leads to rapidly falling pH levels and rising Eh values. All measurements were made immediately after sampl extraction to minimize sample oxidation. Because the change in pH and Eh wit Fe^{2+} oxidation is a well documented effect (Troup et al., 1974; Shapiro, 1966) n attempt was made to document this effect through sequential pH and Eh reading on individual samples.

Specific conductance measurements were made using a Yellow Springs Instru ment model 32 lab/field conductance meter, with a CDC 114 conductance electrod The conductance electrode has a cell constant of 0.1, and was checked for consiste cy on a regular basis using prepared KCl standards.

Subsamples of pore water were collected during squeezing and preserved immediately for ferrous iron determination. The potassium dichromate titration technique (Skoog and West, 1976) was used for ferrous iron determination. This technique is suitable for the wide ranges of iron concentrations encountered in the Waite Amulet tailings. Many replicate measurements were made throughout the sampling, subsequent replication indicates considerable variability throughout the core length. In cases where more than one titration was performed the result presented is an average of all of the determinations from that core section.

B. Pore Gas Sampling

The gas phase of the unsaturated zone of the Waite Amulet was sampled using the technique described by Reardon and Poescente (1984). Narrow diameter (0.64 cm diameter) stainless steel tubes are fitted with machined brass tips and are driven into the tailings. When the appropriate depth is reached the tube is lifted off the tip, and the hole is compacted around the steel tube. Following installation of the tube, pore gas O_2 and CO_2 concentrations are measured using a portable meter. A NOVA model 305LBD gas analyzer was used for CO_2 and O_2 measurements, and a Neutronics Portable O_2 analyzer was used for O_2 measurements. Draeger tubes were also used to provide measurements of CO_2 concentrations. Samples of pore gas were collected and sealed in glass bottles in the field for subsequent analysis with a gas chromatograph in the laboratory. The meters were calibrated with prepared gases before sampling and calibration was checked on a regular basis throughout the sampling using the meter's internal standards. The lower limit of these techniques is about 0.1% O_2 and 0.3% CO_2. O_2 and CO_2 levels lower than this limit were frequently encountered in the Waite Amulet tailings.

The gas sampling technique outlined above is a standard technique that has been used successfully at a number of tailings sites throughout North America. At the Waite Amulet site, however, considerable resistance was encountered as the stainless steel tubes were driven into the tailings. The stainless steel tubes frequently bent or were distorted by the pressure applied during installation. An attempt was made to install the sampling tubes into an augered hole, but this was not found to be satisfactory. As a result of the difficulties encountered in installing the sampling tubes several of the soil gas profiles are incomplete, with refusal often encountered within 1.0 m of ground surface. It is recommended that an alternate

method of gas collection be developed for use in future sampling programs at this site.

RESULTS

The results for each location will be presented separately and discussed, because the results at each site are similar the discussion will be brief.

WA 2

The water table at this site is less than one metre below ground surface. A 100 cm core was taken at this site and a total of 92.5 cm of core was recovered which was divided into 5 equal sections each assumed to be 20 cm. Each section was squeezed and samples were obtained from all sections.

The pH in the near surface is low, in the 3.25 - 3.75 range but rises to a relatively constant value between 5.5 and 6.0 at depths greater than 40 cm. A corresponding decline in Eh (from approximately 600 mV to about 250 mV) is observed (Figure 3). A rise in specific conductance from 11.9 mS to a relatively constant level of about 20 mS occurs between 20 cm and 40 cm. The low pH and high Eh values at shallow depths result from the oxidation of sulphide minerals at this depth. The oxygen concentration in the gas phase of the top 20 cm of the unsaturated zone is about 20%, below this depth the tailings are completely saturated and oxygen movement is limited to oxygen diffusion in the pore water. The low conductance and Fe^{2+} concentrations at shallow depths likely results from the downward displacement of pore waters from these depths by infiltrating rainfall and snow melt.

WA 8

The core tube was driven to a depth of 200 cm, a total of 168 cm was recovered which was divided into 10 equal sections each assumed to represent 20 cm. The two uppermost sections were composed of clay cover material and were not squeezed. The remaining eight sections were squeezed and samples collected. The pH in the upper section of squeezed core is about 3.40 and rises gradually to a value of about 7.0 at 140 cm then remains constant throughout the core (Figure 4). The Eh shows a corresponding decline, from about 450 mV at the tailings surface to about 100 mV at a depth of 120 cm. The specific conductance shows a gradual rise from 15 mS to 28 mS with depth.

At the time of sampling the water table was at the ground surface and gas sampling was not possible.

WA 11

A total of 300 cm of tailings was cored at this site, initially a 100 cm core was taken with 99 cm recovered, this was divided into 5 sections each 20 cm long and squeezed. After the initial 100 cm was squeezed another 200 cm core was collected, with 200 cm recovered, this was divided into 10 sections each 20 cm long. Between corings the hole was filled with nitrogen gas and capped. During the squeezing the core section from 160 - 180 cm was destroyed and so no data are available from this depth.

The pH at this site rises gradually from about 3.85 at the ground surface to a relatively constant value between 5.75 and 6.00 at depths between 1.40 m and 3.00 m (Figure 5). A corresponding gradual but more irregular decline in Eh is observed. Both the specific conductance and the ferrous iron concentrations are low in the near surface area, then rise to a higher plateau at depths between 60 cm and

200 cm, with conductance levels in the 25 - 35 mS range and ferrous iron concentrations of about 7000 mg/L. These are much higher ferrous iron concentrations than were observed at WA 2 or WA 8. Both the specific conductance and the concentration of ferrous iron decline with depth below about 200 cm.

The profiles of O_2 and CO_2 concentrations in the gas phase of the unsaturated zone indicate a sharp change in concentration between 10 and 20 cm. This indicates rapid consumption of O_2 in pyrite oxidation reactions at shallow depths and evolution of CO_2 as a result of carbonate-mineral consuming buffering reactions. The increase in CO_2 concentration below the depth of O_2 consumption indicates that carbonate minerals are dissolving below the depth of direct oxidation. This may be due to the buffering of acidic pore waters that have been displaced downwards by infiltrating precipitation, or buffering of acid generated by indirect pyrite oxidation.

WA 17

A total of 300 cm was cored at this location in two sections. Initially a 100 cm section was cored with 80 cm of core recovered, and divided into 5 equal sections, each assumed to be 20 cm. From this first 100 cm, samples were collected from the intervals from 0-40 cm and from 80-100 cm, no water could be expressed from the core sections from 40-80 cm. A second core was taken from 100-300 cm, with a full 200 cm recovered and divided into 10 equal sections. Pore water samples were expressed from all sections of this core.

The pH in the top 20 cm was about 5.70 (Figure 6), much higher than had been observed in the uppermost section of other sites. Immediately below this the pH falls to about 2.5 and the Eh rises to well over 700 mV. This second core section is similar to what is observed at other locations on the Waite Amulet tailings.

The sampling program was conducted in the late fall of 1987, during a period of mixed snowfall and rainfall. The samples from WA17 were collected shortly after snowmelt had occurred, while samples from most other locations were collected through the unmelted snow cover. The unusual pH and Eh values in the near surface area and the low specific conductance suggest that the water expressed from the uppermost core may reflect recently infiltrated rain or snow melt water. Below the top 100 cm the pH rises to a level between 5.0 and 6.0, similar to the sites discussed previously, and the Eh and specific conductance remain relatively constant.

Many thin layers of cemented tailings were encountered at this site at depths below 20 cm. As a result gas sampling tubes could not be driven to depths greater than 40 cm. The gas profile that was measured between 0 and 40 cm indicates that the O_2 concentration falls sharply between 10 and 20 cm, then declines gradually between 20 and 40 cm (Figure 6). The CO_2 concentration increases sharply from atmospheric levels of about 0.03% at ground surface to over 2% at 20 cm. These are similar to the gas profiles measured at WA 11. One anomalously high concentration of Fe^{2+} was reported at depth of 1.5 m. this value is reported from a single titration and no total iron analysis was conducted, however, sulphate analysis conducted on this sample is in the same range as those from immediately above or below this sample. This indicates that the high value of Fe^{2+} reported is probably due to an analytical error or sampling artifact and so should be disregarded.

WA 20

Locations WA 20 and WA 21 are located on the eastern face of the tailings dam. At WA 20 1 m of tailings was cored with a full 1 m recovery, and divided into 5 equal 20 cm sections and squeezed. Water samples were expressed from each of the sections squeezed.

The pH at this location is below 2.5 for the top 20 cm (Figure 7), then rises to a constant value of about 4.0, lower than at WA 2 and WA 8 where the water table is also quite shallow. The Eh is high, about 700 mV in the shallowest samples, and does not fall below 400 mV in these samples. The low pH and high Eh levels at depth probably arise from the higher O_2 concentrations present at depth at this location. The coarser texture of these tailings may permit O_2 diffusion into the tailings more easily than would be possible through the finer tailings on the top of the impoundment. The CO_2 concentrations in the upper 40 cm of the tailings at this location were at the detection limit of the instruments used for CO_2 measurements. The diffusion of CO_2 out of the tailings is controlled by the same physical factors that, in part, control O_2 diffusion into the tailings, therefore the low CO_2 concentrations and the high O_2 concentrations present at depth at this site are consistent.

WA 21

As with location WA 20 site WA 21 is located on the dam face. A total of 200 cm was cored at this location with 180 cm of core recovered. The recovered core was cut into 10 equal sections each assumed to represent 20 cm. No water could be obtained from the core section between 60 and 80 cm, samples were collected from all other sections.

As at WA 20 the pore-water pH was about 2.5 near the ground surface (Figure 8), then rose to a constant value of about 4.0 between 60 cm and 180 cm, then rose sharply to above 5.0 at 180 cm. The Eh again remained quite high to some depth, remaining above 600 mV to 160 cm indicating oxidized pore waters are present to some depth at this location. The O_2 concentration fell off more rapidly at WA 21 than at WA 20, but about 5% O_2 remained in the gas phase at 30 cm

below ground surface. The CO_2 concentration at all depths at this site was below the meter detection limit, and so is not presented.

WA 22

Site WA 22 is located on the southern edge of the tailings where the water table is deep. A total of 600 cm of core was taken at this location in three sections. The first section was cored from 0-100 cm, with a full 100 cm recovery. Samples were obtained from all sections squeezed except the section from 80 to 100 cm. The second core was taken between 100 and 300 cm, with full recovery, and divided into 10 equal sections. Samples were expressed from all core sections except for the two sections between 180 and 220 cm. The final core was taken from 300 cm to 600 cm, with full recovery. The last 300 cm was divided into 12 sections, each 25 cm long. Samples were obtained from each of the sections squeezed from the final core.

The pH in the top 1 m of core rises sharply from 3.42 in the uppermost section (Figure 10) to about 5.0 at 80 cm, then rises more slowly to a relatively constant value of about 6.4 (Figure 9). The Eh falls in a corresponding manner, however the Eh profile is much more irregular. The Eh is quite high until a depth of about 500 cm, where the water becomes much more reduced. The ferrous iron concentration and the specific conductance are both quite constant, and relatively low at this location.

The oxygen concentration in the gas phase of the unsaturated zone is near atmospheric levels to a depth of 30 cm then falls sharply. The drop in O_2 level at this site occurs at a substantially greater depth than at most other locations, with an O_2 level of greater than 5% at 50 cm. This is attributed to the low moisture content and the coarse grain size of these tailings. The CO_2 concentrations is quite low to a depth of 60 cm, where it climbs to a stable level of about 3%.

WA 24

The core taken at WA 24 intersected 18 cm of clay cover material before entering the tailings. A total of 375 cm was cored at this site in two sections. The first core was driven to 150 cm, with 130 cm recovered. The upper 90 cm was divided into 5 sections each assumed to represent 20 cm and the lower 40 cm was divided into two sections, each assumed to represent 25 cm. Water was expressed from all core sections except for the section from 125 to 150 cm. The second core was driven from 150 to 375 cm with 223 cm of core recovered, this was divided into 25 cm sections and squeezed. No water could be extracted from core samples taken from 150 to 250 cm, and only very small samples were possible between 150 cm and 375 cm.

The pH in this area is quite low, less than 3.20 throughout the first meter (Figure 11). The pH then rises to between 5.7 and 6.0 below 1 m. The Eh is observed to fall in a corresponding manner. At this site low pH levels exist to greater depths than at many of the other locations on the tailings. This was not expected, it was anticipated that the clay cover would limit oxygen diffusion into the tailings and limit pyrite oxidation, leading to an increase in pore-water pH levels as solid phase buffering reactions occurred. Clearly this is not the case; at this location the O_2 level is above 10% up to a depth of more than 1 m. The CO_2 is very low for the upper 70 cm, then rises sharply to over 60% at 120 cm. Site WA 24 is located within an end spill area of the tailings, as is WA 22 and so the tailings at this location are coarser than at many of the other locations on the tailings. The depth of O_2 penetration at other tailings sites has been observed to be greater in areas of coarse tailings in Elliot Lake by Smyth (1981), this may, in part, explain the depth of O_2 penetrations at site WA 24.

SUMMARY AND CONCLUSIONS

The shallow pore water of the unsaturated zone at each of the eight sites samples exhibit low pH, high redox potential conditions, trending to more neutral and reduced conditions at depth. The low pH conditions have resulted from the oxidation of sulphide minerals through reactions of the form

$$FeS_2 + \frac{15}{4} O_2 + \frac{1}{2} H_2O \rightarrow Fe^{3+} + 2SO_4^{2-} + H^+$$

and through the precipitation of ferric hydroxides through reactions of the form

$$Fe^{3+} + 3H_2O \rightleftharpoons Fe(OH)_3 + 3H^+$$

Atmospheric O_2 is the ultimate oxidant for these reactions, therefore the extent of sulphide mineral oxidation and the generation of low pH conditions is controlled by the extent of O_2 entry into the tailings impoundment. The movement of O_2 dissolved in tailings pore water is far slower than O_2 diffusion through the gas phase of the vadose zone and as a result factors that affect the diffusion of O_2 gas in the unsaturated zone will affect the extent of sulphide mineral oxidation.

At locations where the water table is very shallow, for example WA 2 and WA 9, O_2 gas diffusion is limited to the very shallow tailings and consequently sulphide mineral oxidation and low pH conditions are limited to very shallow depths in the tailings. At locations where the water table is deep (eg. WA 17 and WA 22) O_2 gas can penetrate far deeper into the tailings, and, consequently the depth of low pH, high redox potential is also much deeper. A second factor that influences the extent of O_2 gas diffusion into the tailings is the tailings texture, the relationship between soil moisture content and the texture of the soil is well known, and is described by Gillham (1984). Fine-grained tailings, such as those at WA 9 and WA

2 will remain completely saturated well above the water table, while coarser tailings, such as those on the dam face at WA 20 and WA 21 will remain saturated to a much lesser height above the water table. Consequently the extent of sulphide oxidation at WA 20 and WA 21, where the tailings are coarse and the water table is shallow is greater than would be anticipated in an area of finer grained tailings with a similar water table.

Unexpectedly high concentrations of O_2 and low pH and high redox potential conditions exist to a depth about 1 m below the tailings surface at WA 24, the site where clay cover material is present. The reason for this depth of O_2 penetration is not clear, as outlined above the extent of O_2 gas penetration is a function of several parameters, including tailings texture and moisture content. A more complete interpretation of the data from this site will be possible when the complete set of analytical results are considered.

Recommendations for future work include sampling in the spring and summer at two or three locations to determine the extent of seasonal variability in porewater chemistry. It is also recommended that a more suitable gas sampling technique be developed and that gas profiles be measured at many locations on the tailings, both with and without clay cover.

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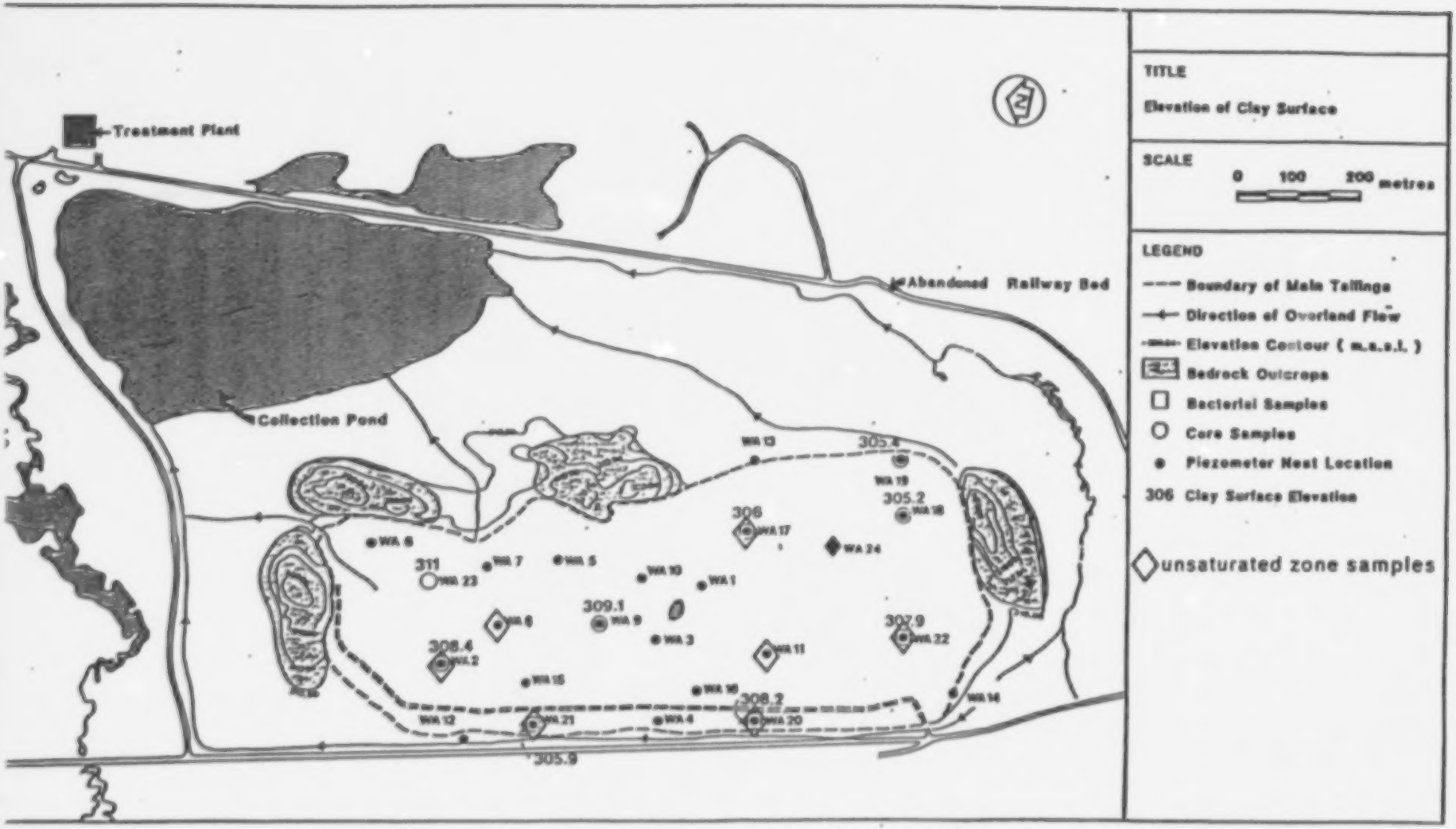

Figure 1. Map of the Waite Amulet tailings site showing location of unsaturated zone sampling sites.

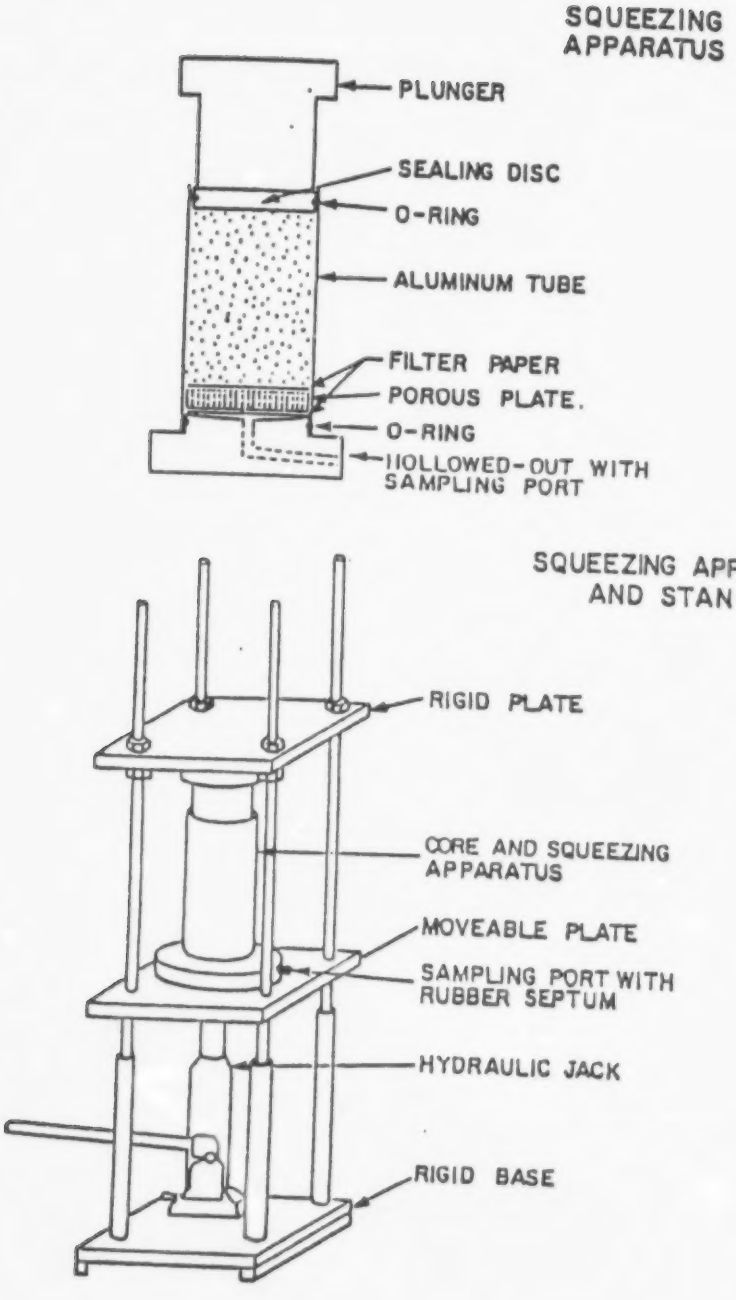

Figure 2. Schematic diagram of squeezing apparatus used for pore water extraction, (from Smyth, 1981).

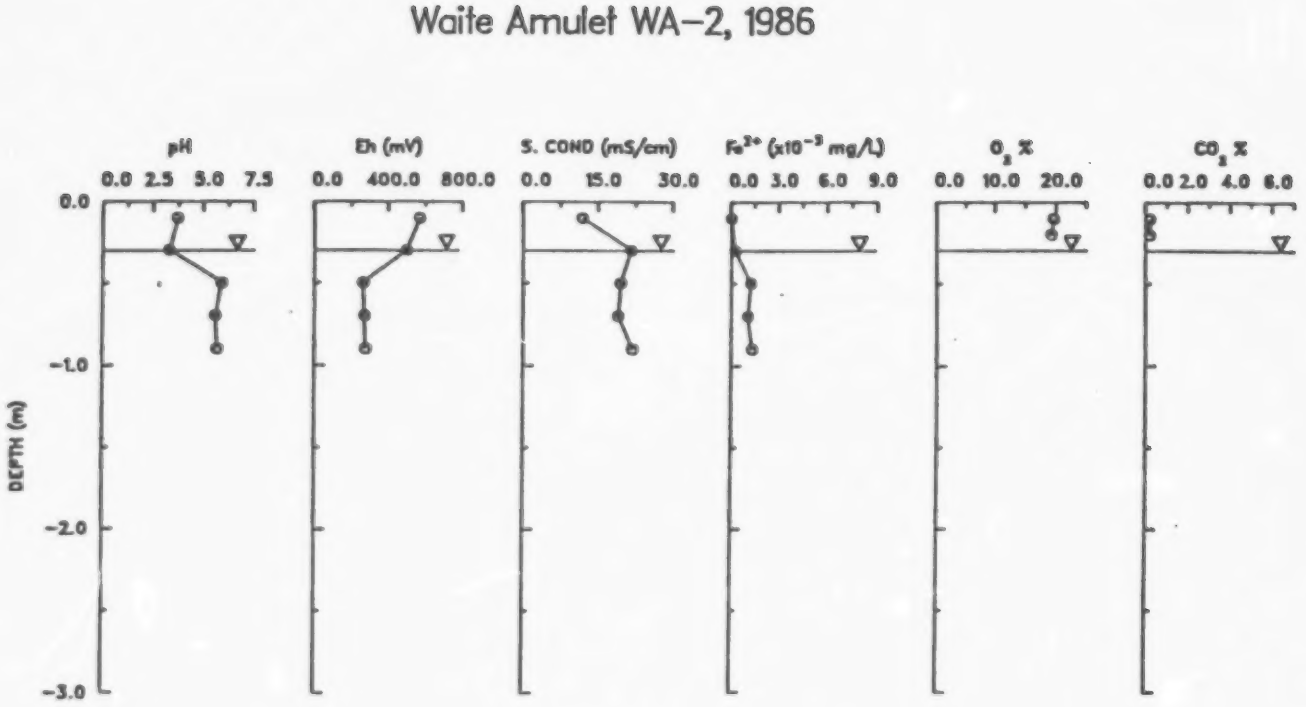

Figure 3. Profile of pH, eH, specific conductance, Fe^{2+} concentration, O_2 and CO_2 concentrations from the unsaturated zone at location WA2, Oct. 1986.

Waite Amulet WA–8, 1986

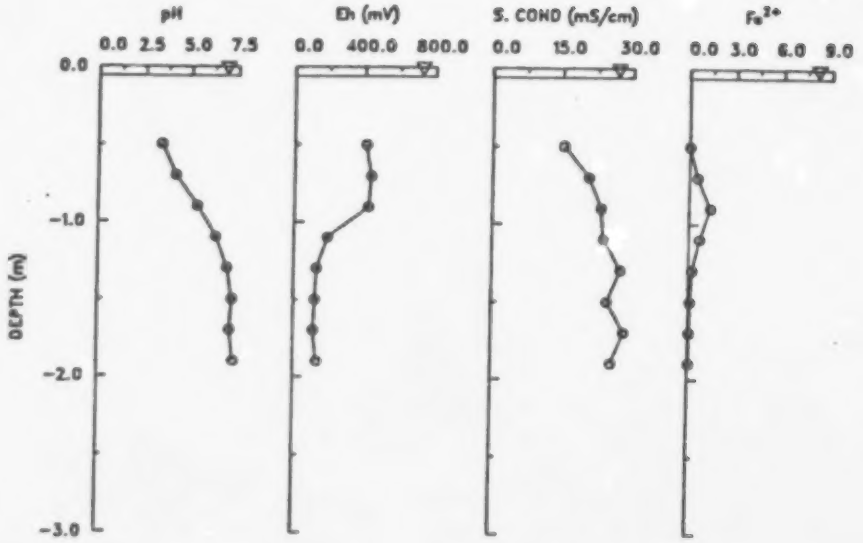

Figure 4. Profiles of pH, eH, specific conductance and Fe^{2+} concentration from location WA8, Oct. 1986.

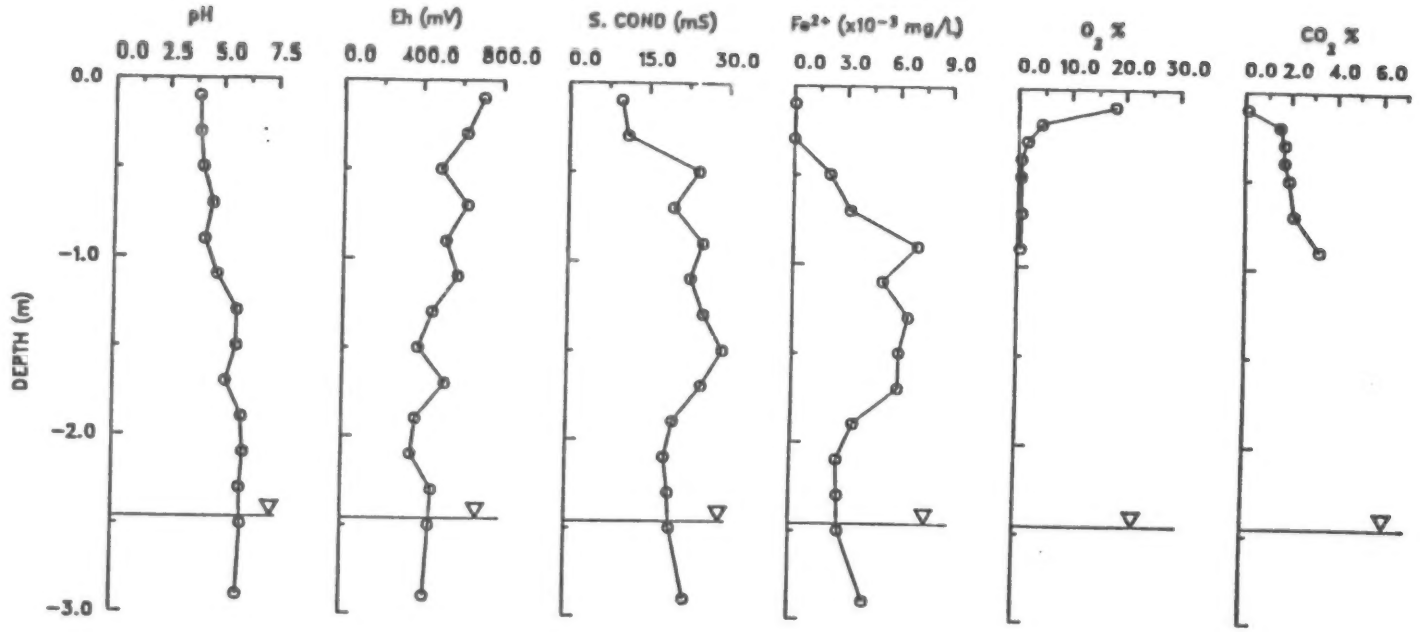

Figure 5. Profiles of pH, eH, specific conductance, Fe^{2+} concentration, O_2 and CO_2 concentrations from the unsaturated zone at location WA11, Oct. 1986.

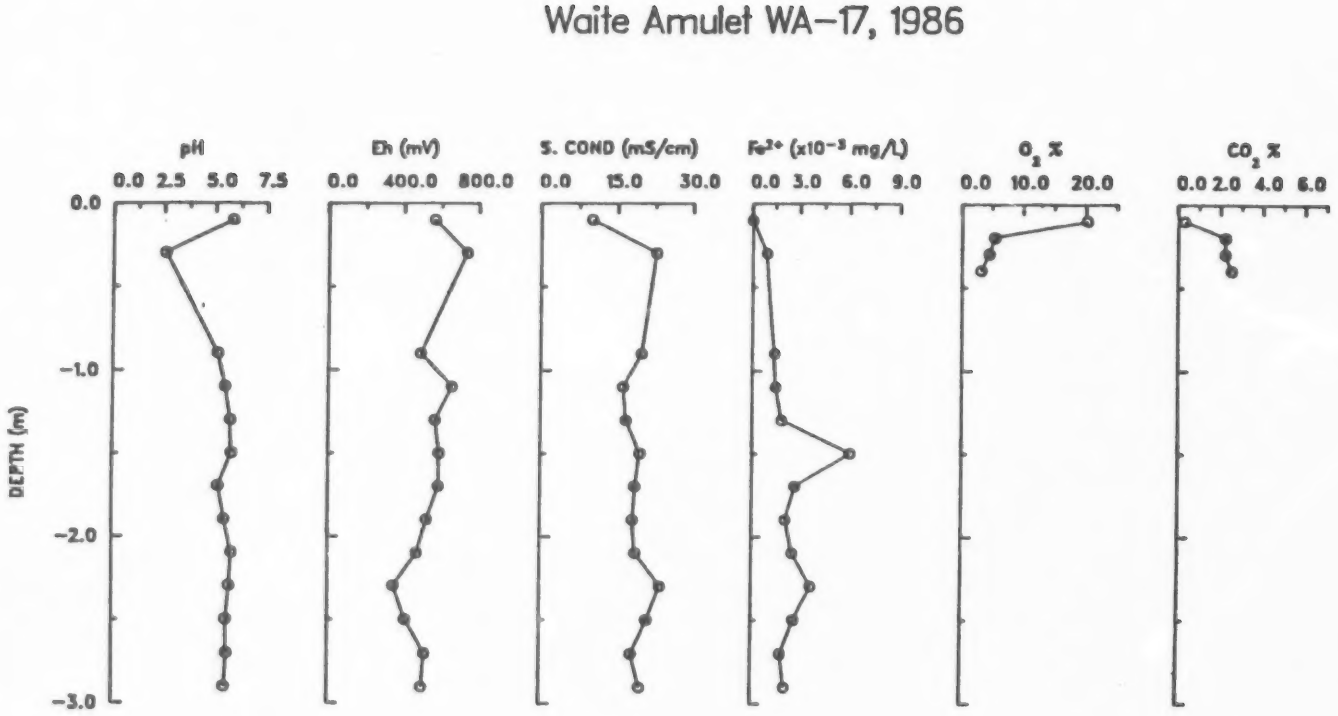

Figure 6. Profiles of pH, eH, specific conductance, Fe^{2+} concentration, O_2 and CO_2 concentrations from the unsaturated zone at location WA17, Oct. 1986. Water-table position as measured in June, 1986.

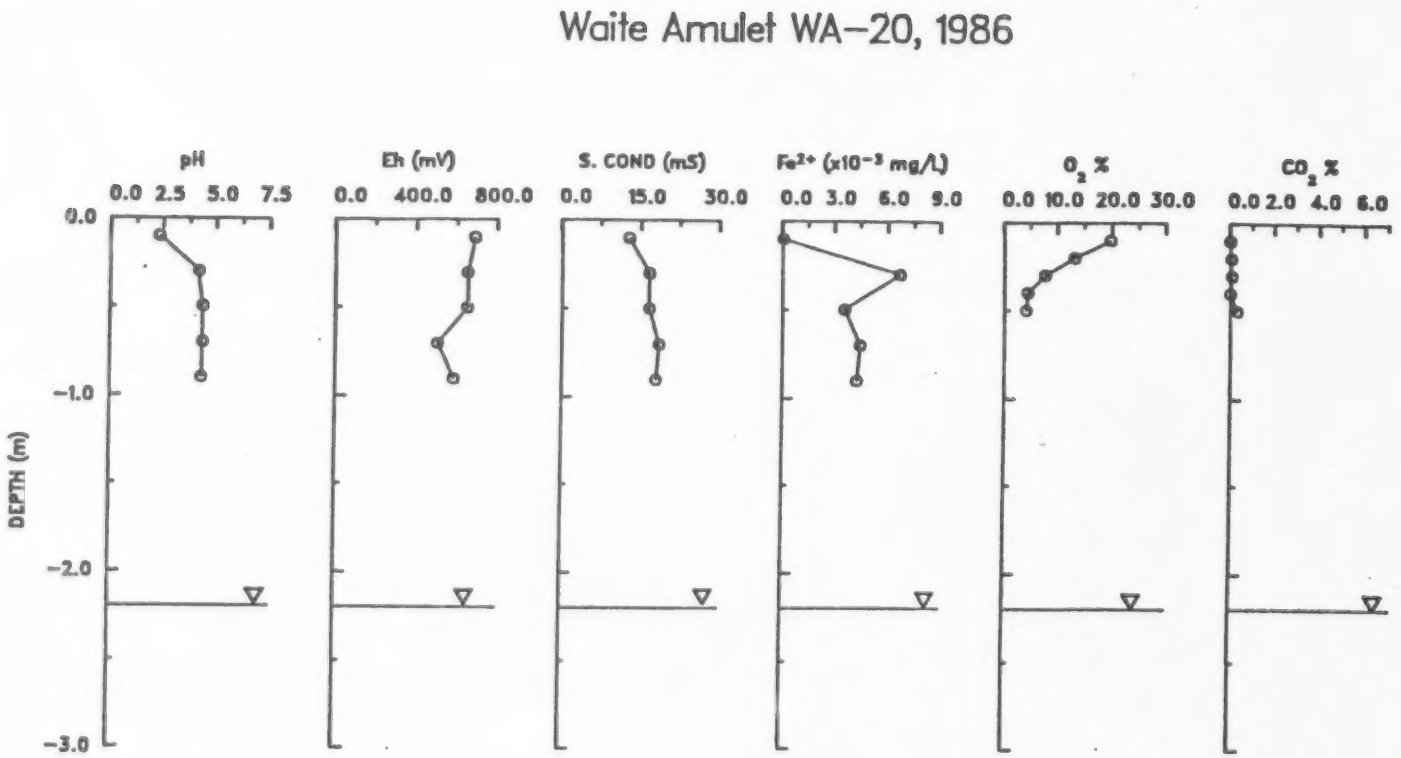

Figure 7. Profiles of pH, eH, specific conductance, Fe^{2+} concentrations, O_2 and CO_2 concentrations from the unsaturated zone at location WA20, Oct. 1986.

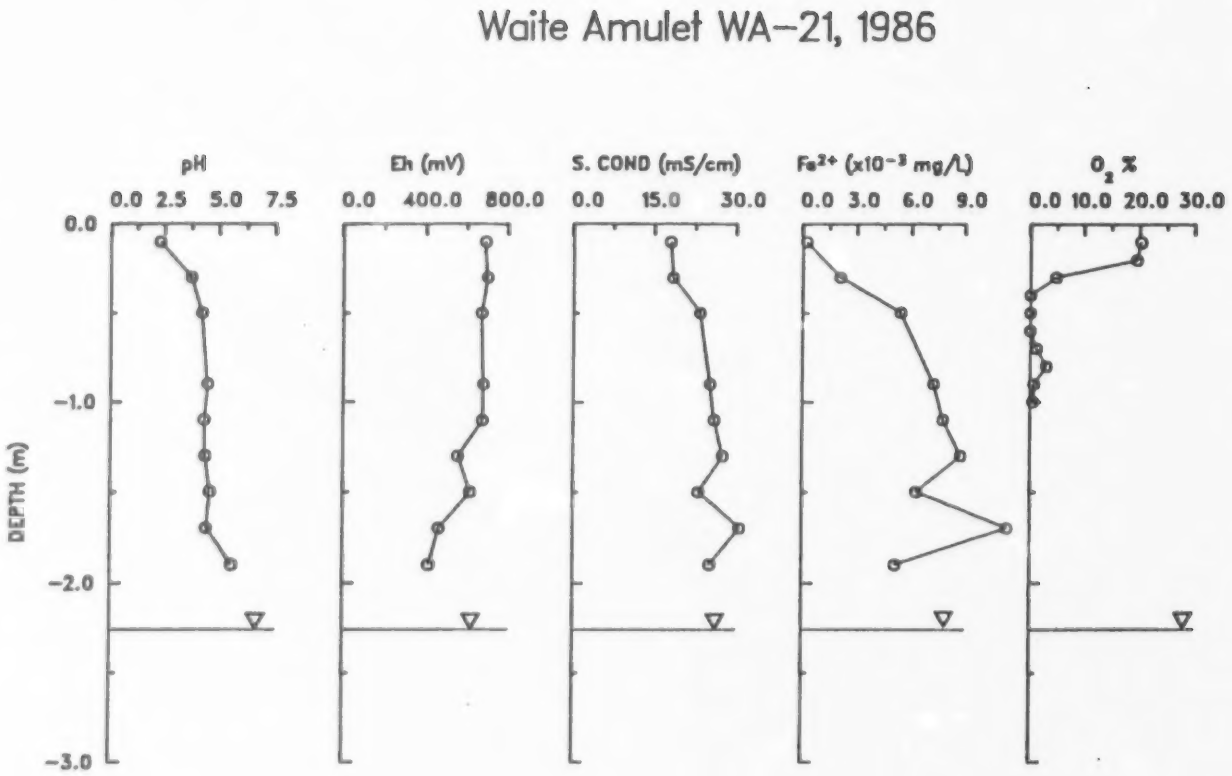

Figure 8. Profiles of pH, eH, specific conductance, Fe^{2+} concentration, and O_2 concentration from the unsaturated zone at location WA21, Oct. 1986.

Waite Amulet WA–22, 1986

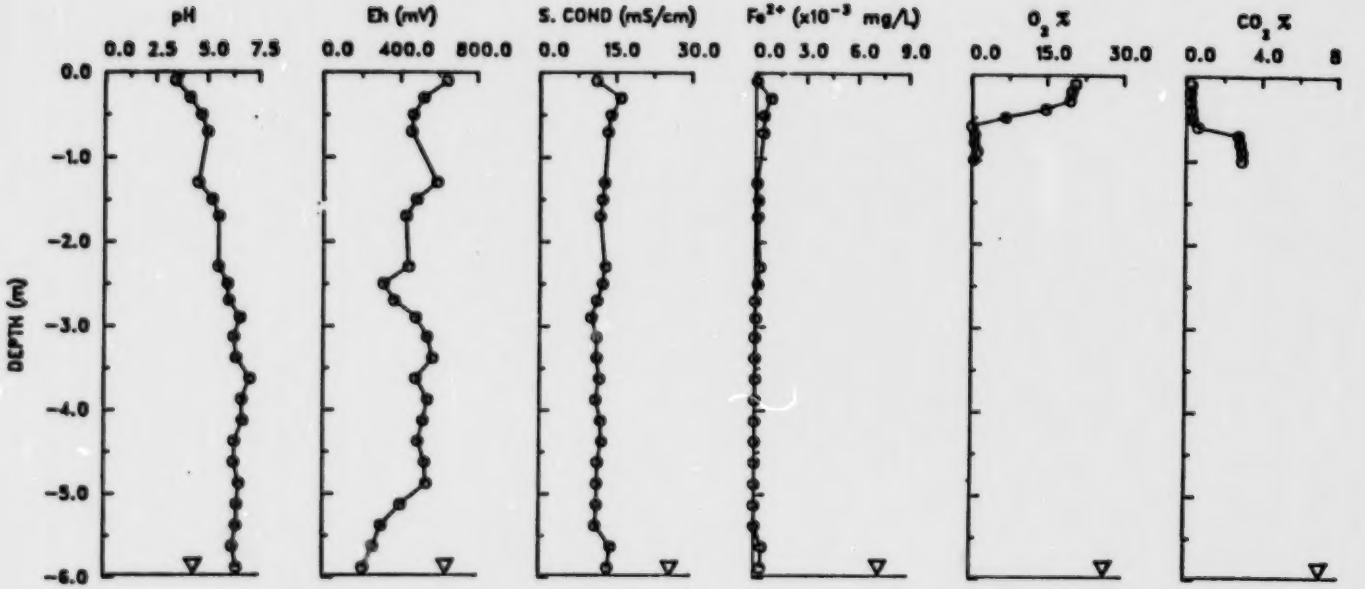

Figure 9. Profiles of pH, eH, specific conductance, Fe^{2+} concentration, O_2 and CO_2 concentrations from the unsaturated zone at location WA22, Oct. 1986. Water-table position as measured in June, 1986.

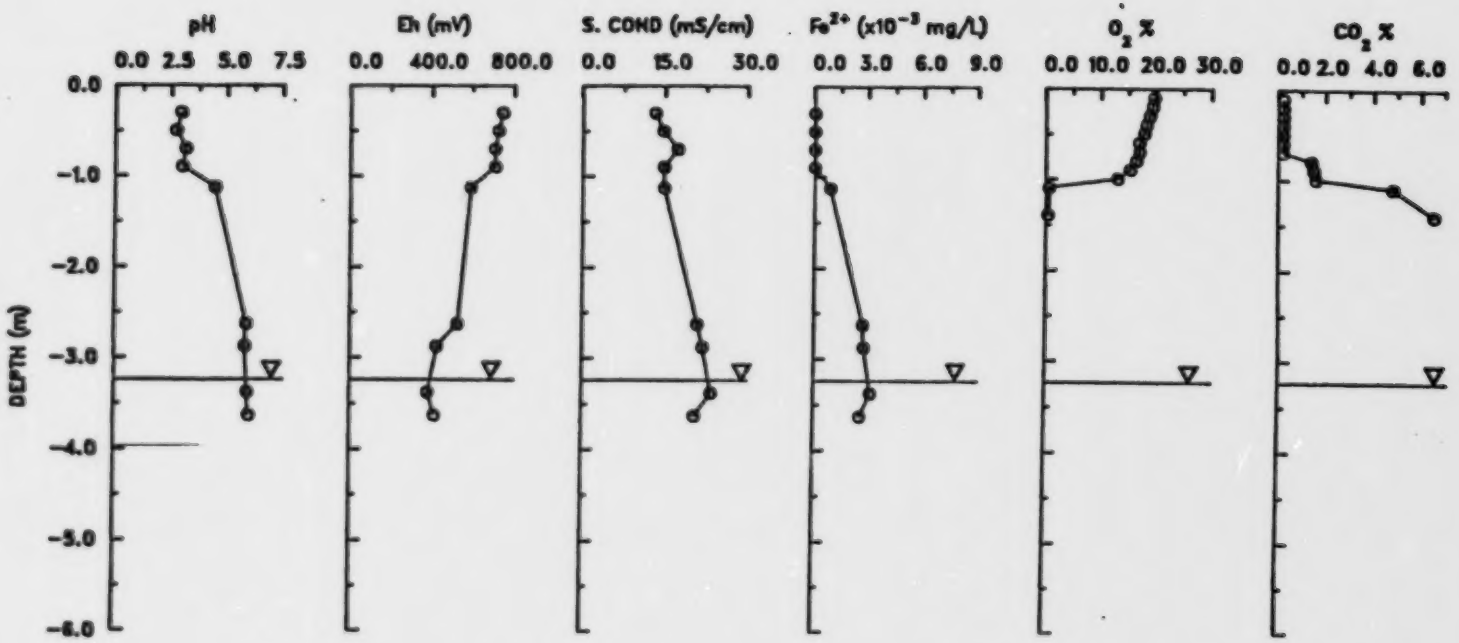

Figure 10. Profiles of pH, eH, specific conductance, Fe^{2+} concentration, O_2 and CO_2 concentrations from the unsaturated zone at location WA24, Oct. 1986.

Table 1. Field geochemistry results from WA 2, 1986.

WA 2

Depth (m)	pH	Eh (mV)	S. Cond. (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10	3.70	568	11.9	12	19.6	0.2
0.20					19.2	0.2
0.30	3.27	496	21.6	243		
0.50	5.89	262	19.5	1210		
0.70	5.58	270	19.0	1030		
0.90	5.68	276	21.9	1230		

Table 2. Field chemistry results from WA 8, 1986.

WA 8

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)
0.50	3.38	408	15.2	17
0.70	4.14	437	20.5	515
0.90	5.32	423	23.2	1330
1.10	6.32	190	23.8	670
1.30	6.94	128	27.5	205
1.50	7.21	119	24.6	105
1.70	7.10	112	28.3	66
1.90	7.31	133	25.6	45

Table 3. Field geochemistry results from WA 11, 1986.

WA 11

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10	3.85	702	9.7	33	18.0	0.1
0.20					4.3	1.5
0.30	3.90	620	11.0	8.8	1.7	1.7
0.40					0.6	1.7
0.50	4.04	490	24.4	2040	0.6	1.9
0.70	4.51	625	19.7	3200	0.8	2.1
0.90	4.14	519	25.3	7040	0.6	3.2
1.10	4.75	581	23.0	5060		
1.30	5.67	453	25.5	6530		
1.50	5.68	382	29.1	6010		
1.70	5.18	520	25.2	5670		
1.90	5.94	372	20.0	3460		
2.10	6.03	350	18.5	2580		
2.30	5.89	459	19.4	2690		
2.50	5.96	448	19.8	2760		
2.90	5.79	425	22.7	4230		

Table 4. Field geochemistry results from WA 17, 1986.

WA 17

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10	5.82	562	10.0	6.4	20.1	0.3
0.20					5.3	2.2
0.30	2.54	734	22.6	907	4.4	2.2
0.40					3.1	2.5
0.90	5.11	487	19.7	1400		
1.10	5.47	655	16.1	1475		
1.30	5.74	565	16.7	1860		
1.50	5.80	588	19.5	6000		
1.70	5.15	584	18.5	2670		
1.90	5.45	522	18.1	2090		
2.10	5.81	469	18.7	2530		
2.30	5.69	347	23.6	3665		
2.50	5.53	411	21.0	2635		
2.70	5.58	515	18.0	1845		
2.90	5.46	499	19.7	2105		

Table 5. Field geochemistry results from WA 20, 1986.

WA 20

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10	2.30	686	12.8	58.5	19.7	BD
0.20					13.1	0.05
0.30	4.16	650	16.6	6650	7.6	0.07
0.40					4.3	BD
0.50	4.35	649	16.6	3560	4.0	0.3
0.70	4.35	501	18.5	4430		
0.90	4.30	582	17.9	4250		

Table 6. Field geochemistry results from WA 21, 1986.

WA 21

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)
0.10	2.28	688	17.9	213	20.2
0.20					19.4
0.30	3.72	698	18.4	2060	4.7
0.40					0.0
0.50	4.21	669	23.4	5380	0.0
0.60					1.2
0.80					3.0
0.90	4.47	679	25.3	7240	0.7
1.00					0.5
1.10	4.32	675	26.1	7770	
1.30	4.38	554	27.6	8750	
1.50	4.59	614	23.2	6270	
1.70	4.42	461	30.7	11400	
1.90	5.57	412	25.3	5120	

Table 7. Field geochemistry results from WA 22, 1986.

WA 22

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10	3.42	640	11.2	81	20.5	0.25
0.20					19.7	0.2
0.30	4.13	517	15.9	886	19.4	0.2
0.40					14.6	0.25
0.50	4.68	462	14.0	475	6.6	0.3
0.60					0.0	0.6
0.70	4.97	454	13.4	450	0.6	2.7
0.80					0.5	2.8
0.90					1.1	2.9
1.00					0.4	2.9
1.30	4.53	589	12.8	100		
1.50	5.20	482	12.4	1830		
1.70	5.52	426	12.0	1510		
2.30	5.51	440	13.0	275		
2.50	5.96	308	12.5	160		
2.70	6.04	365	11.4	14		
2.90	6.57	478	10.3	55		
3.13	6.28	537	11.4	6		
3.38	6.40	566	11.4	4		
3.63	7.06	478	11.9	38		
3.88	6.66	539	11.2	41		
4.13	6.70	515	12.2	7		
4.38	6.31	489	12.4	6		
4.63	6.28	525	11.6	11		
4.88	6.54	533	11.5	BD		
5.13	6.43	400	11.5	7		
5.38	6.40	299	11.2	49		
5.63	6.22	256	14.3	466		
5.88	6.42	205	13.7	400		

Table 8. Field geochemistry results from WA 24, 1986.

WA 24

Depth (m)	pH	Eh (mV)	S. Cond (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)
0.10					19.5	0.2
0.20					19.2	0.2
0.30	2.92	742	13.1	5	18.7	0.2
0.40					18.1	0.2
0.50	2.69	721	14.6	9	17.7	0.2
0.60					16.8	0.2
0.70	3.12	705	17.2	6	16.9	0.2
0.80					16.3	1.4
0.90	2.97	706	14.7	8	15.2	1.5
1.00					12.9	1.6
1.10					0.6	4.8
1.13	4.44	587	14.8	864	0.4	6.5
1.40						
2.63	5.87	524	20.9	2705		
2.88	5.82	422	21.9	2770		
3.38	5.93	379	23.5	3160		
3.63	6.00	413	20.5	2580		

Table 9. Ferrous iron titration results from all cores.

LOCATION	DEPTH (m)	NUM OF REP.	REP 1 (mg/L)	REP 2 (mg/L)	REP 3 (mg/L)	MEAN (mg/L)
WA 2	0.10	2	15.8	9.39		12.6
	0.30	1	243.1			243.1
	0.50	3	972	1570	1100	1214
	0.70	2	1030	1030		1030
	0.90	2	1210	1380		1295
WA 8	0.50	3	13.8	17.7	20.1	17.2
	0.70	1	593	437		515
	0.90	2	1170	1148		1325
	1.10	2	544	791		668
	1.30	2	226	184		205
	1.50	2	113	98		105
	1.70	2	81	52		67
	1.90	3	53.8	40.8	42.6	45.7
WA 11	0.10	3	53	26.5	19.4	33
	0.30	2	13.4	4.1		8.8
	0.50	2	2740	1600		2035
	0.70	2	3490	2910		3200
	0.90	2	7340	6730		7035
	1.10	2	5080	5040		5060
	1.30	2	6620	6440		6530
	1.50	2	6140	5870		6005
	1.70	2	6100	5830		5970
	1.90	2	3440	3480		3460
	2.10	2	2900	2260		2580
	2.30	2	2310	3060		2685
	2.50	2	2750	2770		2760
	2.90	2	4360	4100		4230
WA 17	0.10	1	6.35			6.35
	0.30	3	80.1	2560	80	907
	0.90	1	1400			1400
	1.10	2	1310	1640		1475
	1.30	1	1860			1860
	1.50	1	6000			6000
	1.70	1	2670			2670
	1.90	1	2090			2090
	2.10	2	2500	2560		2530
	2.30	2	3370	3960		3665
	2.50	2	2560	2710		2635
	2.70	2	1640	2050		1845
	2.90	2	2050	2160		2105

Table 9 (cont'd). Ferrous iron titration results from all cores.

LOCATION	DEPTH (m)	NUM OF REP.	REP 1 (mg/L)	REP 2 (mg/L)	REP 3 (mg/L)	MEAN (mg/L)
WA 20	0.10	3	89.5	78	8.06	58.5
	0.30	2	4590	8710		6650
	0.50	2	3430	3690		3560
	0.70	1	4430			4430
	0.90	2	3720	4782		4251
WA 21	0.10	2	245	180		213
	0.30	1	2060			2060
	0.50	2	5320	5440		5380
	0.90	1	7240			7240
	1.10	2	8290	7240		7765
	1.30	2	8450	9050		8752
	1.50	1	6270			6270
	1.70	2	12700	10000		11350
	1.90	2	3930	6300		5115
WA 22	0.10	1	81			81
	0.30	2	592	1180		885
	0.50	2	953	980		977
	0.70	2	360	539		450
	1.30	2	140	66.3		103
	1.50	2	161	204		183
	1.70	3	63.5	257.5	201.7	151.2
	2.30	1	277			277
	2.50	2	164	205	109	159
	2.70	1	13.8			13.8
	2.90	1	55.3			55.3
	3.13	1	6.07			6.07
	3.38	1	4.14			4.14
	3.63	1	38.1			38.1
	3.88	1	4.14			4.14
	4.13	1	6.9			6.9
	4.38	1	5.53			5.53
	4.63	1	11.05			11.05
	4.88	0				
	5.13	2	8.84	6.08		7.46
	5.38	2	85.6	12.4		49
	5.63	2	464	467		466
	5.88	2	338	461		400
WA 24	0.30	1	4.7			4.7
	0.50	1	9.12			9.12
	0.70	1	5.52			5.52
	0.90	1	8.3			8.3
	1.13	2	757	970		864
	2.63	2	2750	2660		2705
	2.88	2	2720	2820		2770
	3.38	2	3060	3260		3160
	3.63	1	2580			2580

APPENDIX D

1986 National Symposium on Mining, Hydrology, Sedimentology, and Reclamation
(University of Kentucky, Lexington, Kentucky 40506-0046 – December 8-11, 1986)

Geophysical and Biohydrogeochemical Investigations of an Inactive Sulphide Tailings Basin, Noranda, Quebec, Canada

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Abstract Geophysical and biohydrogeochemical investigations were carried out at an inactive copper-zinc mine tailings site, Waite Amulet, in Noranda, Quebec, Canada. Geophysical investigations consisted of seismic, electromagnetic conductivity and electrical resistivity surveys to determine the thickness of the layers above bedrock and to map conductivity variations within the tailings and the immediate outlying area. Biohydrogeochemical investigations consisted of installing multilevel piezometer nests to determine groundwater flow patterns and porewater chemistry, obtaining solid core samples and characterizing for physical, chemical and mineralogical parameters, and iron oxidizing and sulphate reducing bacterial counts.

The geophysical survey indicated a bedrock ridge extending under the tailings from the northeastern outcrop which may act as a porewater boundary layer. The survey also indicated a 2 to 20 m clay layer underlying the main tailings dam. Preliminary results of the saturated zone porewater chemistry have indicated three major zones of high electrical conductivity varying between 1000 to 12,000 µs and pH between 3.4 to 8. Lower pH and high metal and sulphate concentrations were obtained in a shallow zone near the water table. With depth, the concentration of metal and sulphate ions decreased and pH increased below the water table. The underlying clay layer is relatively impervious and most of the seepage from the tailings is probably exiting from the sides of the impoundment dam.

In the unsaturated zone, the pH increased with depth from 3 to 6. Bacterial analysis showed a strong presence of thiobacillus ferro-oxidans in the upper 2 m of tailings (8000 to >100,000 MPN/g). Sulphate reducing bacteria were not detected in a majority of samples below the water table.

Introduction

Throughout the base metal mining regions of Canada, there are approximately 1.8 billion tonnes of sulphide tailings covering an areal extent in the order of 9000 ha[1]. Most of the tailings are placed in extensive tailings impoundments located above ground in shallow depressions and bounded by high impoundment dams. The tailings consist of finely ground solids residue from the host rock, sulphides of iron (pyrite, marcasite, pyrrhotite, arsenopyrite, etc., which are not removed in the milling process) and trace amounts of other base metal sulphides. Upon weathering and with the availability of moisture and oxygen, these sulphide tailings oxidize producing highly acidic leachates containing high concenetrations of dissolved solids. With precipitation and recharge events, these oxidation reaction products from tailings porewater are transported via surface run-off and sub-surface seepage to the neighbouring water courses, thereby seriously affecting their natural quality. In order to meet environmental regulations, all the effluent from a tailings basin

is collected and treated prior to its discharge to natural water systems. In terms of long-term management goals of these highly reactive sulphide tailings, an eventual abandonment scheme is to be developed which will require very little human intervention in terms of perpetual maintenance and treatment so as to develop a safe and predictable walk-away situation. These problems of sulphide tailings are being addressed by a joint industry/government sponsored Reactive Acid Tailings Program (RATS), established in 1985 with the aim of developing techniques that will enable the base metal mining industry to ultimately abandon acid generating tailings areas in a predictable, cost effective and environmentally acceptable manner.

The reactive acid tailings program consists of four technical components:

1) predictive techniques;
2) tailings disposal systems;
3) reclamation; and
4) effluent control.

Details of these components are described by Bell[2] in a separate study report.

Under the predictive technique, existing inactive tailings sites are to be surveyed for their physical, chemical, biological and hydrogeochemical parameters governing the biohydrogeochemical evolution of these basins. The study will provide base line data for a generic model development which will enable, in a practical and predictive way, evaluation of the long-term behaviour of sulphide tailings under a wide range of conditions, e.g., bare, vegetated and other covers, etc. For the initial phase of this study, geophysical and biohydrogeochemical investigations are being carried out at an inactive copper-zinc tailings site. The geophysical work consisted of:

1) a seismic survey to determine the thicknesses of various layers above bedrock;
2) an electromagnetic survey; and
3) an electrical resistivity survey to map conductivity variations within the tailings and the immediate outlying area.

The biohydrogeochemical work consisted of:

1) hydrological investigations to determine groundwater flow patterns and other hydraulic parameters;
2) geochemical investigations pertaining to solid and liquid phases; and
3) biological investigations dealing with the profiles of iron-oxidizing and sulphate-reducing bacterial populations.

Preliminary results of these investigations are described in this report.

Site Description

For this study, an inactive Waite Amulet tailings site located approximately 20 km north of Noranda, Quebec (48°15'N, 79°03'W) was selected (Figure 1). The site consisted of approximately 6.5 million tons of high sulphide tailings spread over an area of 80 ha in total, of which approximately 40 ha are contained in an elevated main dam and the rest in tailings spills in the lower area. The Waite Amulet mine/mill complex operated for about 40 years and ceased operation in October 1982. The ore milled at the site came from two principal mines: Waite Amulet and West MacDonald, and consisted primarily of chalcopyrite, marmatite, pyrite, pyrrhotite, diabase and feldspar with total sulphide content ranging between 80-90%. The mill produced copper and zinc concentrates by flotation and at later stages also operated a pyrite flotation circuit. Tailings from several other mines were also deposited at the Waite Amulet tailings site.

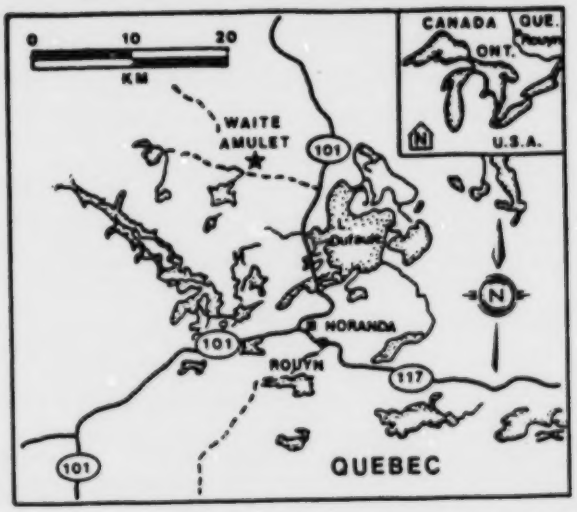

Fig. 1 - Location of the Waite Amulet tailings site.

The tailings, in the slurry form, were deposited by spigotting in the summer and end spilling during the winter. The perimeter dam, consisting of coarse cycloned tailings, is benched and is approximately 12 m above the surrounding area. A portion of the area is bounded by bedrock outcrops primarily in the northeast portion of the site (Figure 2). Prior to this study, it was believed that the tailings were deposited on a varved clay layer approximately 6 m thick and underlain by the bedrock.

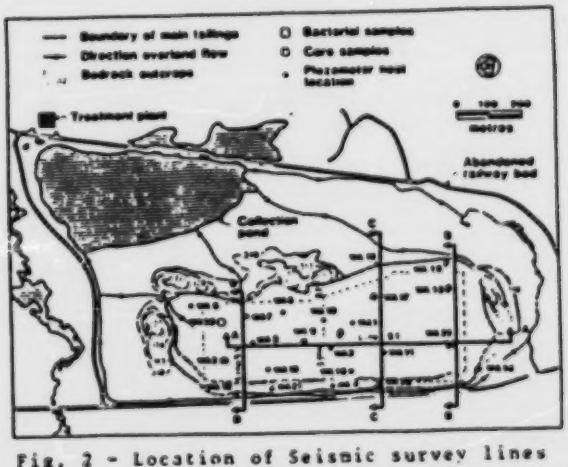

Fig. 2 - Location of Seismic survey lines S1, S2, S3, E.M. conductivity grid pattern, piezometer nests, solid and bacterial sample boreholes and vertical cross-section lines on the main tailings dam.

Large scale reclamation of the tailings area commenced in 1978, and by 1982 most of the tailings area had been revegetated. The acidic seepage from the tailings area is presently being collected and diverted to a holding pond northeast of the tailings where the water is treated in an automated computer controlled treatment plant and then discharged to Lake Dufault, east of the tailings area (Figure 2). At present the site is owned and operated by Noranda Mines Ltd. (Horne Division), Noranda, Quebec.

Methods

Geophysical Methods.

As a part of the preliminary hydrologic survey of the White Amulet site, a geophysical survey was undertaken to determine the thickness of the tailings and the underlying clay, topographic variations in the underlying bedrock and electrical conductivity variations across the tailings. The geophysical investigations consisted of seismic refraction, electromagnetic and electrical resistivity surveys.

Seismic refraction data give detailed vertical information along traverses. Electromagnetic surveys give broad lateral information across the site. Resistivity soundings are used to give site specific variations in vertical electrical conductivity. The penetration depth of these methods are variable and are used to examine variations in electrical conductivity across the site. A large number of measurements are taken in a detailed grid pattern across the site to establish lateral variations (Figure 2).

Seismic Refraction. The seismic refraction technique measures variations in the velocity that a shock wave or pulse propagates along boundaries of geologic units. It is assumed that seismic velocities of various units increase with depth as is generally the case.

A vibration is created by either a sledge hammer blow or a small explosion. To detect the vibration, a series of geophones is used. Typically, 12 geophones are placed at regular intervals from the source of vibrations. Close to the source the first vibration reaching the geophone has travelled in a straight line along the surface. A plot of travel time versus distance from the source produces a straight line with a slope that is the inverse of the material velocity. As the distance between the source and geophone is increased, a critical distance is reached where the first vibration to arrive at the geophone is no longer the one travelling along the surface. This vibration has travelled down to a deeper, higher velocity layer, moved along it and has come back to surface. At distances greater than the critical distance, the difference in first arrival travel path for subsequent geophones is an increase in distance along the lower layer. The slope of the time-distance plot becomes the inverse of the higher velocity in this layer.

Using the source at either end of the geophone spacings, the interface of the high velocity layer, can be calculated using the delay time method presented by Redpath[3].

Electromagnetic Terrain Conductivity Measurement. The Electromagnetic (EM) system used in this study was designed by Geonics. It is a two coil system. A current moving through the transmitting coil creates a primary electromagnetic field. This field penetrates the ground and induces a small current flow within the earth. The small current creates another (the secondary) EM field. The properties of the secondary field are a function of the electrical conductivity of the ground. Therefore, by detecting the combined primary/secondary field with another coil (the receiver) and removing the effects of the primary field, the ground electrical conductivity is determined.

The instrument yields a bulk conductivity for the earth, down to a penetration depth controlled by the inter coil spacing and orientation.

Electrical Resistivity Measurements. Direct current resistivity soundings measure the apparent resistivity of the ground through which an induced electrical current passes. The resistivity of the ground varies according to the grain size and water content of the material through which the electrical current passes. A current flow is induced through the ground between two electrodes. Two other electrodes are used to measure the potential voltage drop in the ground between the two electrodes. The depth of penetration of the electrical current is directly proportional to the distance between the current electrodes. By systematically increasing the distance between current electrodes, vertical variations in electrical conductivity, and hence variations in stratigraphy, can be measured.

Hydrological Investigations.

The hydrological investigations consisted of installing piezometers at various locations, single or in multilevel piezometer nests throughout the site. By monitoring piezometric pressure heads, groundwater flow directions and hydraulic gradients can be established.

Piezometer Installation. Piezometers installed in the tailings were a modified Casagrande drive-point piezometer, developed at the University of Waterloo[4]. It was constructed entirely of PVC material. A porous polyethylene cartridge with a 50 micrometer pore size was used for the piezometer screen. The porous cartridge formed a sleeve over a 15 cm by 3 cm schedule 80 PVC perforated barrel. The porous cartridge was placed between the drive point tip and female coupling and sealed with a silicone compound. Piezometers were installed by hand using a percussion drill in areas of fine grained material and shallow water table. In other places, the installation was done using a track mounted CME75 drill and hollow stem auger. Holes were augered to 1 m above the desired depth of the piezometer, and the latter then driven by hand 0.5 to 1.0 m below the lead auger to allow the installation of the piezometer in relatively undisturbed tailings. At a given site a series of piezometers was installed at different depths with vertical spacing of approximately 1.5 m between piezometers at each nest. Piezometers installed in clay underlying the tailings were slotted scheduled 40 PVC pipe ranging in length from 0.6 m to 3 m. These piezometers were installed inside the hollow stem augers and were gravel packed with 0.6 cm

washed pea gravel and a bentonite seal placed above the gravel pack. Figure 2 shows the piezometer locations. A total of 58 piezometers was installed at 23 nest locations.

After installation, the water level in the piezometers was measured routinely to establish their response and to establish steady-state after installation and initial clean-out. By monitoring the water levels, groundwater flow directions and hydraulic gradients were established over the tailings area. Hydraulic conductivities of the tailings material surrounding each piezometer were determined using the Hvorslev rising head test. The water column in a piezometer pipe is pumped out and the rate of inflow of water is measured during the recovery. With the measured recovery rate and the shape of the piezometer (i.e., length and diameter of the water intake zone), the hydraulic conductivity of the tailings in the immediate vicinity of the piezometer can be determined.

Geochemical Investigations.

For geochemical investigations both tailings solid core and water samples were obtained. The solid samples were characterized for principal physical parameters, e.g., moisture content, grain size, porosity, etc., and mineralogy. Chemical profiles were measured for both solid and liquid samples.

Solid Sampling. Solid sampling was performed at nine locations (Figure 2). Six of the locations were on top of the main tailings area, while the other three locations were on the bench area of the tailings dam. The samples were obtained by a specially designed continuous soil sampler which fitted inside a hollow stem auger of I.D. 10.8 cm. The sample barrel was a split barrel which was advanced with auger advancement during drilling. The position of the sample barrel was adjusted to have a portion of it ahead of the augers, or just up inside the lead auger. The adjustment depended upon the hardness and cohesiveness of the material being sampled. The continuous sampler system did not turn with the augers as it was advanced, and was in fact pushed ahead similar to obtaining a Shelby tube sample. The sampler was 1.5 m in length and 8.25 cm in diameter. Depending on the material being sampled, the length of the samples collected (i.e., lengths of auger advancement) varied from 0.75 m in regions of high water content and relatively incohesive material, to 1.5 m in the unsaturated and clay zones. The solid cores were sub-sampled for physical, chemical and biological characterizations.

Water Sampling. After installation, all the piezometers were cleaned, either by pumping out, or lifting the water with a gas lift pump using compressed nitrogen. Fresh water samples were obtained using a peristaltic pump, filtered in the field with 0.45 μm membrane filter and a glass fibre pre-filter. Temperature, pH, Eh, electrical conductance, acidity, alkalinity and Fe^{+2} for water samples were measured in the field. The samples were then acidified with HCl (final concentration 2% acid) and preserved for laboratory analyses for major cations and anions.

Biological Investigations.

The biological investigations consisted of analyzing the solid core samples for iron-oxidizing 'thiobacillus ferro-oxidans' and sulphate reducing organisms. Two of the nine core samples, one from the main tailings, and the other from the perimeter dam were analyzed. For bacterial counts, the core samples were sub-sampled. These sub-samples were then placed in sterilized sample containers and refrigerated prior to analysis. Care was taken not to expose samples to the outside environment which would be detrimental to the bacterial populations, especially to the oxygen-sensitive sulphate reducers.

The method of enumeration for Thiobacillus ferro-oxidans and sulphate reducers was a 5 x 5 most probable number (MPN) where 5 replicates of 5 dilutions of each sample were employed. The MPN method, in each case, provided an estimate of the number of bacteria per gram dry weight of tailings sample.

Results and Discussion

Geophysical Results

Seismic Survey. The seismic survey provided representative cross-sections of the site along the three survey lines. Over most of the tailings, 4 layers were identified as:

Layer 1 was a continuous surface unit with a seismic velocity of 300 ms^{-1}. This layer represented unsaturated and very poorly consolidated tailings or fill.

Layer 2 with a velocity of the order of 600 ms^{-1} represented saturated tailings. The unit was continuous and varied in thickness from 2 to 10 m over the site.

Layer 3 was identified as a clay layer based on the drilling results. The seismic velocity is 1100 ms^{-1} and the thickness varied from less than 2 m to 21 m. The elevation of the top of layer 3 varied by 5 m over the site.

Layer 4 was identified as bedrock with a velocity of 3980 ms^{-1}. The bedrock surface was irregular with over 15 m of relief across the site.

Core logs from holes WA9 and WA22 (Figure 2) provided the control for the seismic results as these holes were near the seismic lines.

Electromagnetic and Electrical Resistivity Surveys. These provided the apparent thickness of tailings and depth to the bedrock, but only very approximately as the data could only be interpreted for a two layer system.

Based on these results and drilling logs, the site can be described as:

Tailings: The thickness varied from 2 m to about 15 m. The thickness increased to the south-west, filling any depressions in the surface of the clay. The seismic velocity of the tailings was uniform and more typical of unsaturated materials. The electrical conductance was variable but always high, about 100 to 400 mS.

Clay: The surface of the clay was moderately irregular as it sloped to the south and west across the site. Its thickness varied from 2 to 20 m, thinning on bedrock highs. It has a fairly uniform seismic velocity.

Bedrock: The topography of exposed bedrock around

the site and underneath was extremely variable. Bedrock elevations decreased to the south-south east across the site. At least two, and possibly three, ridges trending north east-south west appeared to extend from bedrock outcrops to the tailings.

Groundwater Flow System

Figure 3 shows the general water table configuration across the tailings area obtained in October 1985. The water table varied from just below the ground surface in the north and central portions of the site to 5.5m below ground surface in the southern part. Figures 4 and 5 show the vertical water levels (porewater pressures) distribution across the two cross-sections AA along the northsouth, and CC along the central eastwest directions, respectively. The data showed wide variations in hydraulic gradients across the site. The horizontal gradients varied from 0.007 in the south west (i.e., WA14) to 0.04 in the north west (i.e., WA12, WA21). The vertical gradients ranged from almost non-existent at WA22 to greater than 0.5 at WA2.

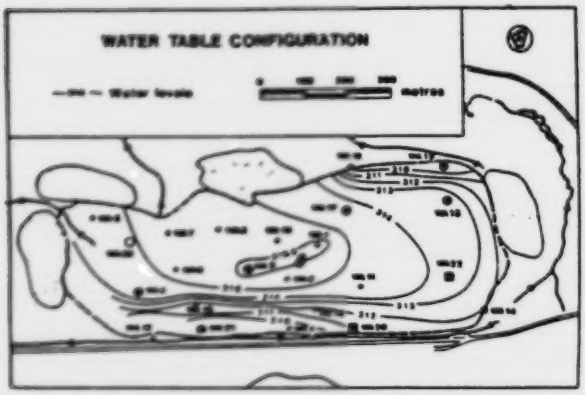

Fig. 3 - Water Table elevation contours in the main tailings dam.

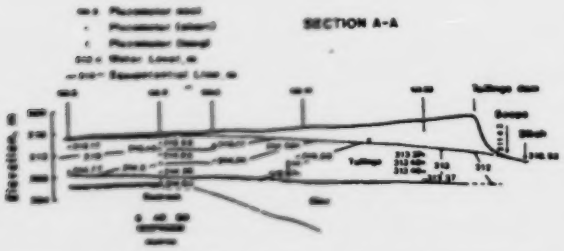

Fig. 4 - Porewater pressure contours along the north-south vertical cross-section AA.

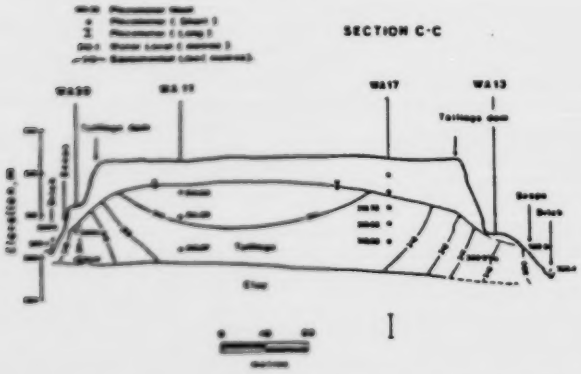

Fig. 5 - Porewater pressure contours along the central east-west vertical cross-section CC.

Based on the water table configurations and vertical water level profiles, it appears that porewater within the tailings is generally moving outwards from the centre of the tailings through the coarse grained tailings dam and discharging into the surrounding drainage ditch, either directly, or as a seepage across the tailings dam. The elevation of water level and flow along these seepage lines increased very quickly after rainfall events.

Because of its low permeability, the underlying clay would act as a barrier to the downward movement of porewater from the tailings in the south portion of the site. In the north portion, it appeared that there was little hydraulic connection with the shallow bedrock in the north-east, but there may be good hydraulic connection in the north-west direction where a high hydraulic conductivity zone below the tailings was observed.

Hydraulic conductivities ranged from 9×10^{-7} cm/sec to 1.4×10^{-3} cm/sec. Low hydraulic conductivities $\sim 10^{-6}$ cm/sec were generally found in the north end of the tailings where fine grained tailings were deposited. The highest hydraulic conductivities ($\sim 1.2 \times 10^{-4}$ - 1.4×10^{-3} cm/sec) were generally found in the south end of the tailings and along the perimeter dams. The porewater horizontal velocities within the tailings ranged from 0.4 cm/y to 5 m/y. Tailings porewater velocities across the tailings dam were calculated up to 35 m/y indicating the majority of the tailings porewater to exits from the dam sides.

Porewater Chemistry

Figures 6 and 7 show the pH and electrical conductance profiles (measured in October 1985) along the cross-section AA and CC, respectively.

The results showed that the pH below the water table across the site was generally greater than 6. At locations close to the water table on the dam bench (WA14, WA4-2), the measured pH was between 4.7 and 6.0. In the shallow water table zone, WA11 on the main tailings, the measured pH was below 6. At these locations, lower pH values ranging between 3.4 to 5.7 were obtained in early June 1986. This is probably caused by the increased oxidation activity near the shallow water table zone during warmer climatic conditions. There is little evidence of vertical profile trends in pH below the water table other than the slightly lower pH in the porewater zone just below the water table.

Electrical conductance of water within the tailings varied from about 1000 µs to 12,000 µs. At most locations a decrease in the electrical conductance with depth was observed. This decrease was generally a factor of two to three. The main exceptions to this general trend were at locations WA9 and WA2, where most elevated electrical conductivity values were obtained in the middle of

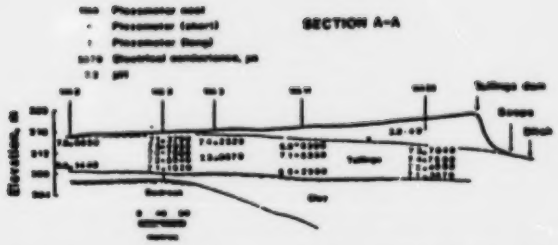

Fig. 6 - pH and electrical conductance profiles along the vertical cross-section AA.

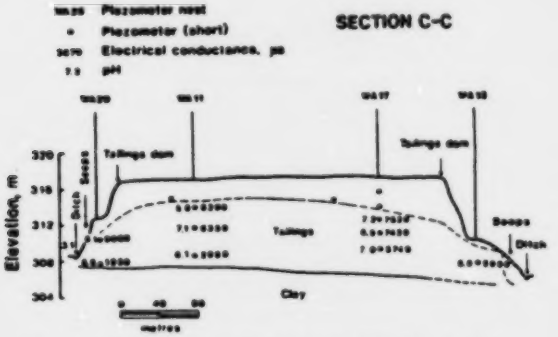

Fig. 7 - pH and electrical conductance profiles along the vertical cross-section CC.

the saturated zone. These locations also had the strongest downward vertical gradients observed on the site suggesting deeper penetration of the recharge water.

Lower pH and higher electrical conductance values were observed in seepage waters around the perimeter of the dam compared to those in the adjacent area tailings porewater. This suggested further oxidation of the tailings porewater as it seeped out.

Figure 8 shows the chemical profiles of tailings porewater as a function of depth for the WA22 site. Concentrations of SO_4^{-2}, Fe, Ca, Mg, Al, Mn, Ni, Co, Zn, and Pb all decreased with depth below the water table as the neutral pH zone was approached. This is caused by the neutralization of the acidic porewater, and hence precipitation of metal hydroxides as it migrates downward. The degree of neutralization depended upon the presence of resident alkaline buffers in the tailings.

Solid Phase Analysis

Figure 9 shows the solid phase pH and bacterial counts for thiobacillus ferro-oxidans and sulphate reducers reported as most probable numbers (MPN/g) as a function of depth for two bore holes WA20 and WA22. For WA20, mineral compositions for pyrite, pyrrhotite, and altered oxidation product goethite are also shown [5].

The bacterial results showed a strong presence of iron oxidizing thiobacillus ferro-oxidans above the water table at both locations. Their activity profile indicated the most active oxidation strata

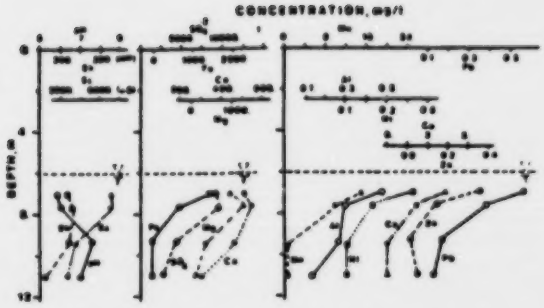

Fig. 8 - Saturated zone tailings porewater chemical profiles for pH, Eh, Ec, SO_4^{-2}, Fe, Ca, Mg, Mn, Al, Ni, Co, Zn and Pb.

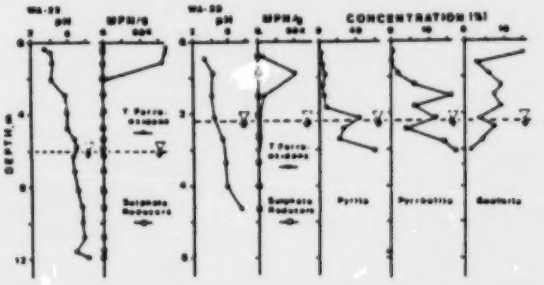

Fig. 9 - Solid phase tailings profiles for pH, thiobacillus Ferro-oxidans and sulphate reducers, pyrite, pyrrhotite and Goethite.

in the vadose zone. Petruk[5] obtained similar results for oxidation profiles from mineral compositions for WA20 where oxidation has been completed in the uppermost layer, progressing faster in the unsaturated zone above the water table and progressing slowly near the water table in the saturated zone. For most of the solid samples analyzed, sulphate reducers were not present.

Further studies are being conducted dealing with the diffusion of oxygen in the unsaturated zone and the effect of various covers, porewater and solid phase chemistry, mineralogy and movement of contaminants from tailings porewater to the underlying clay layer and bedrock. The results of these investigations will be reported when available.

Acknowledgements

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THE EFFECTIVENESS OF VEGETATION IN CONTROLLING ACID GENERATION IN BASE METAL TAILINGS

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ABSTRACT

Noranda Inc., which currently owns 18 mines in Canada and the United States, maintains a high degree of commitment to environmental protection. Reclamation research in the early 1970's at Noranda Waite Amulet site led to a successful vegetation program. However, the expected benefits of vegetation in reducing acid generation at Waite Amulet have not been realized.

Further research efforts have been undertaken at Heath Steele Mines Ltd., Newcastle, N.B., Waite Amulet, Rouyn-Noranda, P.Q., and a high carbonate tailings site in Ontario. The program involves a characterization of the geochemistry and hydrogeology and an evaluation of the parameters which control oxidation. Modelling tools will be evaluated for predicting the geochemical behaviour of these tailings with time and under varying reclamation scenarios.

Direct vegetation of reactive tailings has not restricted oxygen diffusion nor has it limited water infiltration. Consequently, oxidation of sulphide tailings is occuring, acid water containing heavy metals is being generated and complex geochemical processes of neutralization, precipitation, co-precipitation and adsorption are taking place to ameliorate pore water quality. The upper 1 to 2 m zone of oxidation is influenced by such factors as the water table and the sulphide content and particle sizing of the tailings. Infiltrating water due to precipitation and snowmelt transports pore water containing dissolved metals through the tailings and into the groundwater and surface seepage systems.

1.0 Introduction

Environmental protection is an important element of Noranda Inc's operations. In 1986, the Board of Directors approved an environmental policy which states the following:

> Noranda Inc. operations will strive to be exemplary leaders in environmental management by minimizing the environmental impact on the public, employees, customers and property, limited only by technological and economic viability. The following principles are basic to achieving this environmental objective:
>
> 1. The potential risks of new projects to employees, the public and the environment must be assessed so that effective control measures can be foreseen and taken, and all parties made aware of these facts.
>
> 2. Noranda group operations will implement site specific environmental, health, hygiene, safety and emergency response policies in the spirit of guidelines issued by Noranda Inc. as well as in conformation to applicable laws and regulations.

3. Noranda group operations will constantly evaluate and manage risks to human health, the environment and physical property.

4. Noranda group operations will be subject to periodic environmental, health, hygiene, safety and emergency preparedness audits.

5. A report on environment, health and hygiene, safety and emergency preparedness will be presented annually to the Board.

Though the policy is recent, the corporation has maintained a high degree of commitment to environmental protection over the years.

Noranda Minerals Inc., one of four Divisions within the corporation, currently operates, maintains or is decommissioning 18 mines in Canada and the United States. Of these, 10 are operating, 3 are being maintained in a closure mode awaiting improved metal prices or sale, and 5 are closed and are either being decommissioned or being prepared for sale. Among operating mines, 6 may enter the reclamation phase within 2-5 years unless additional reserves are identified through continuing exploration. Noranda Inc. tailings areas total approximately 3500 ha, of which 50% is classified as reactive due to the presence of sulphides.

Mining activities which may have a significant impact on the design of a reclamation plan - vegetation and acid generation being two of the parameters here-include:

- o open pit operations in which case rock dumps may be formed - the rock representing the capping/stripping and boundary material surrounding the mineralized zone which must be removed to expose the ore, and

- o development of a tailings pond which confines the remaining gangue material after the minerals are extracted from the ore.

Tailings and mine rock may be reactive, acid generating sources - the balance determined by the acid generating and consuming capacity of the host material. Today, techniques exist which can determine a positive or negative potential for acid generation. These technologies were not available when some of the early reclamation work was undertaken.

2.0 The Early Waite Amulet Vegetation Experience

It was not many years ago when a vegetative cover over a tailings area or a rock dump was considered to be <u>the</u> panacea. Noranda's history in this approach began in the

1960's when the current Horne Division initiated work on the Waite Amulet tailings pond near Rouyn-Noranda, Quebec. The objectives of these early efforts were to:

- control fugitive dust due to wind erosion of the surface;
- control surface water erosion;
- improve site aesthetics;
- improve the water balance by an active vegetative cover which would intercept, evaporate and evapotranspirate moisture thereby preventing its entry into and flow through the tailings mass;
- control acid generation.

The 41 ha Waite Amulet dam contains approximately 5.9 Mt of tailings with a 60-90% sulphide composition, pyrite being the main mineral. Tailings were deposited from 1933 to 1962 with the exception of one shutdown period.

In the late 1960's, surface water quality monitoring revealed evidence of acid generation due to the oxidation of iron sulphides. Neutralization of acidic water was

initiated at that time. By 1969, the Horne Division had decided upon the need for a vegetative cover to control tailings dusting and acid generation as well as to improve site aesthetics.

Surface pH of the tailings ranged between 2.2-3.0. Starting in 1969, an experienced contractor undertook the reclamation work. Lime at 11.2 t/ha, fertilizer and seed were added based upon experience at other sites and although a green tinge developed, the vegetation died back within a month. A second attempt was made the next year with a higher limestone addition rate (15.7 t/ha) with an unfortunate similar result - total failure. Noranda then decided it was time for a new approach.

Limestone neutralization tests were conducted in the laboratory and a tailings acid demand of 56 t/ha of lime was indicated. In 1972, 10 100 m^2 plots were established and 112-168 t/ha of limestone and varying fertilizer and seed mixtures were applied. Although results were promising, costs were quite high. Variability in test plot performance introduced some technical uncertainty and consequently the Horne Division was reticent about proceeding with another full scale reclamation attempt.

3.0 Noranda/University of Guelph Program - Vegetation

Noranda Inc. initiated a five year research program with the University of Guelph, beginning in 1974, to evaluate the variability of sulphide tailings and how this could affect plant growth and to improve the technique for assessing growth potential of these sulphide materials. Although copious data were generated, correlations between growth potential and chemical and physical characteristics of tailings were not evident! Conventional metallurgical and agricultural analyses did not elucidate the problem. What did develop from the research program, however, was a rapid growth room assessment technique whereby a relatively large number of tailings samples with varying applications of lime, fertilizer and seed could be evaluated. This technique has subsequently been applied within Noranda Inc. companies and some reclamation projects based on these laboratory scale assessments have been successfully carried out.

Waite Amulet was vegetated in stages from 1978 to 1981 using agricultural limestone at a rate of 45 t/ha and lush, self-sustaining and maintenance free vegetation exists to date.

4.0 The Effectiveness of Waite Amulet Vegetation

Stream water quality monitoring on and adjacent to the Waite Amulet site continued and in 1982 an expanded sampling program was undertaken. The news was not good. Acidity, iron, zinc and copper concentrations averaged as high as 8000, 2400, 115 and 14 mg/L respectively at some individual sampling stations located on four streams draining the site and pH generally ranged between 2.5-3.0. An improvement in water quality has not been evident.

Qualitatively, the vegetative cover has been effective in controlling fugitive dust and surface water erosion, as well as in improving site aesthetics. Indeed, these objectives have been fully achieved. A reduction in the rate of acid generation which can be ascribed to vegetation is believed to be minimal, if any took place at all. An active, water consuming surface cover will tend to depress the water table and consequently the potential for oxygen penetration is enhanced. However, it must be stressed that baseline data collection was inadequate for a proper, quantitative evaluation of acid generation and water balance after reclamation was completed.

By 1984, an acid storage pond and a modern waste water treatment plant were constructed at a cost of 1.8 M$. The lime neutralization facility has been operating efficiently on a seasonal basis at a cost of 0.2 M$ annually.

5.0 The Current Noranda Inc. Research Effort

With such a significant inventory of reactive tailings requiring decommissioning, practical and economical technology to control acid generation needs to be developed. The number of properties approaching the decommissioning phase within the next five years adds a sense of urgency to the quest for a better understanding of processes involved in acid generation and for environmentally efficient and reasonably cost effective technology.

Consequently, Noranda Inc. initiated discussions with the federal Department of Energy, Mines and Resources (CANMET) and other mining companies to formulate a national research program. The Reactive Tailings (RATS) program, now funded equally between the sponsoring industry and CANMET, began to evolve in 1984.

Currently, Noranda Inc. is sponsoring research on two fronts - first, a RATS study at the Waite Amulet tailings site being conducted by Centre du Recherche Noranda and CANMET and second, a University of Waterloo, Institute for Groundwater Research program. In general, the broad objectives of these efforts are to:

- characterize the geochemistry within reactive tailings;

- identify the processes which control the geochemistry;

- determine, evaluate and demonstrate the mechanisms which control the geochemical reactions; and

- predict the geochemical behaviour of reactive tailings under various reclamation scenarios.

Several technical papers focussed on these broad objectives have already been published on the Waite Amulet study program by Siwik and Dave, 1987, and Dave et al. 1986, and others will follow. A series of papers will also be generated by D.W.Blowes on the University of Waterloo program.

The technical discussion which follows includes information from the Waterloo investigations as they pertain to the vegetation/acid generation relationship.

The sites included here are:

- Heath Steele Mines Limited, Newcastle, New Brunswick (managed by Brunswick Mining & Smelting Corporation Limited)

- Waite Amulet Tailings Site, Rouyn-Noranda, Quebec (managed by the Horne Division)

- a high carbonate tailings site in Ontario, formerly owned by a Noranda Inc. company; and

- Nordic Mine Tailings, Elliot Lake, Ontario, not a Noranda Inc. site but one researched by the University of Waterloo.

The field methods utilized by the University of Waterloo are outlined in Appendix A. A description of geochemical processes is provided in Appendix B.

5.1 Heath Steele Mines Limited, Newcastle, New Brunswick

The 4 ha tailings pond at Heath Steele Mines Limited was examined by Boorman and Watson, 1976 of the New Brunswick Research and Productivity Council. Although no reclamation work has been initiated on these tailings, the location was included in the University of Waterloo program to examine the geochemistry ten years after the earlier research effort. Deposition of tailings containing 85% sulphide minerals, mostly pyrite and pyrrhotite, was discontinued in 1964. Pore water chemistry in the vadose and groundwater zones was determined as well as gas concentrations in the unsaturated tailings layer.

Low pH and extremely high levels of Fe^{2+} and specific conductance were recorded at this site (Figure 1). The low pH, high Fe^{2+} conditions were observed to be directly related to oxygen penetration depths. Very high concentrations of several metals (Cu, Pb, Zn, Ni) were observed near the surface in the vadose zone (Figure 2). These metals were probably released to solution by the oxidation of sulphide minerals. This tailings impoundment has not had the benefit of a vegetation program, but the processes controlling pore water evolution appear to be the same as at the other sites investigated. Very high concentrations of metals in solution are attributed to the high sulphide content of the tailings.

5.2 Waite Amulet Tailings, Rouyn-Noranda, Quebec

The Waite Amulet tailings impoundment is an ideal location for investigating the geochemistry within a reactive tailings mass since the site has barren, directly vegetated and clay capped and vegetated regions.

Results from the Quebec field site indicate that pyrite oxidation has generated low pH, high Fe^{2+} and high specific conductance levels in the vadose zone of the tailings. Near the surface and within the unsaturated zone, the pore water pH level is generally below 2.5. Redox potential is quite

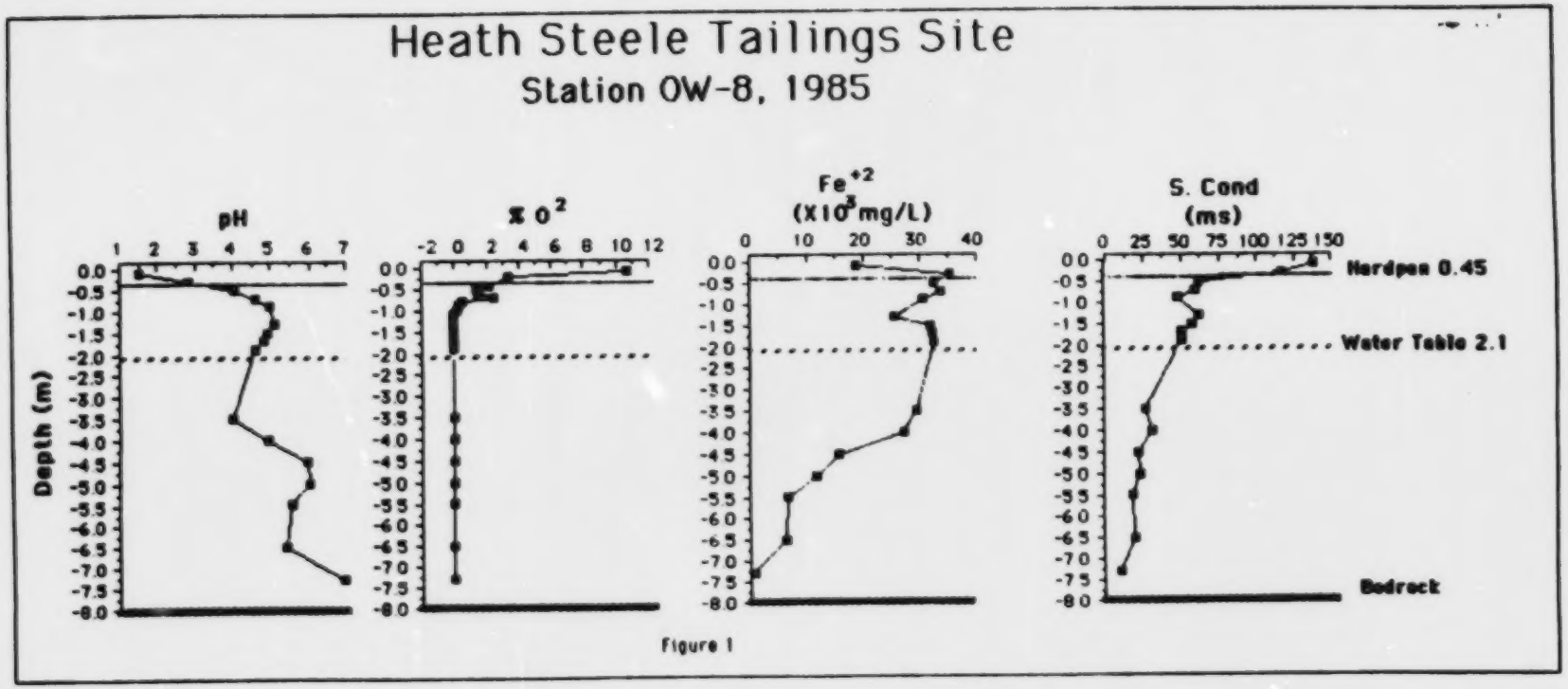

Heath Steele Tailings Site
Station OW-8, 1985
pH
% O2
Fe+2
(X10-3mg/L)
S. Cond
(ms)
Depth (m)
Hardpan 0.45
Water Table 2.1
Bedrock

Figure 1

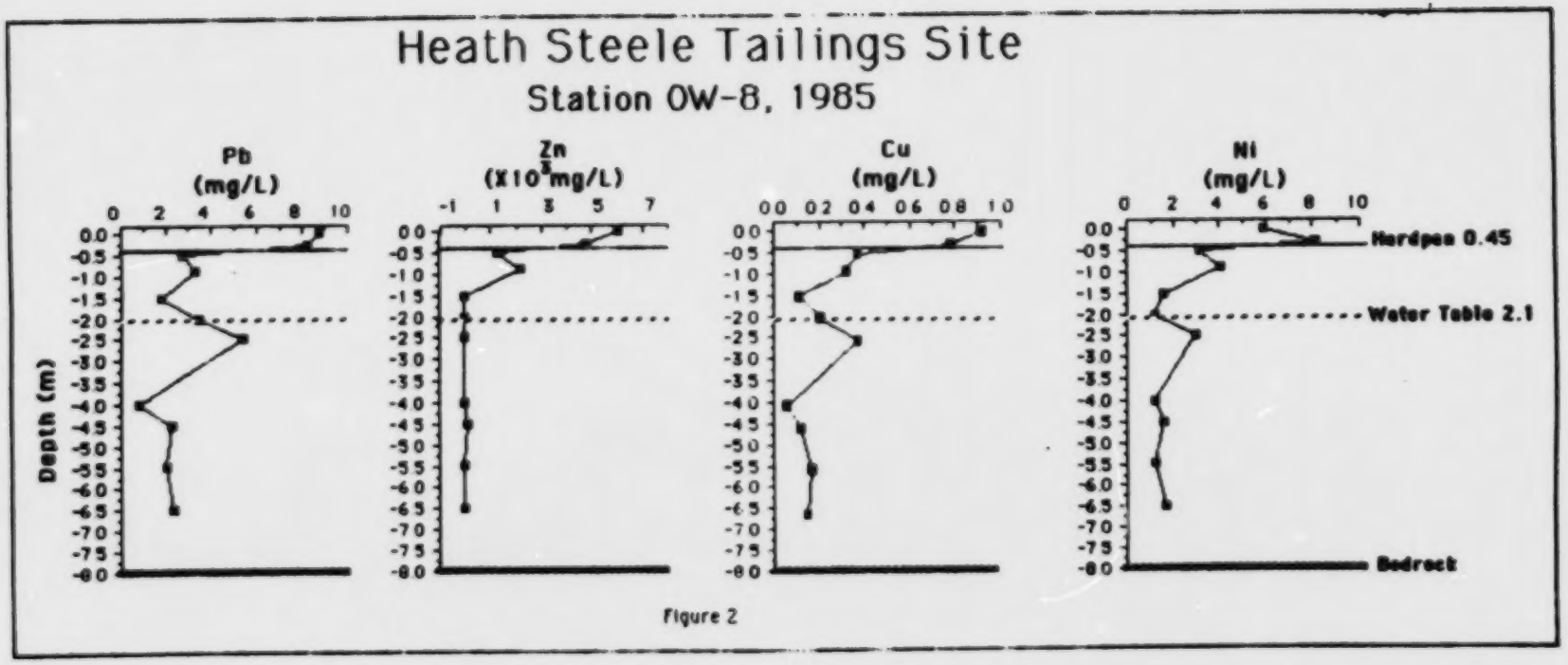

Heath Steele Tailings Site
Station OW-8, 1985
Pb
(mg/L)
Zn
(X10³mg/L)
Cu
(mg/L)
Ni
(mg/L)
Depth (m)
Hardpan 0.45
Water Table 2.1
Bedrock

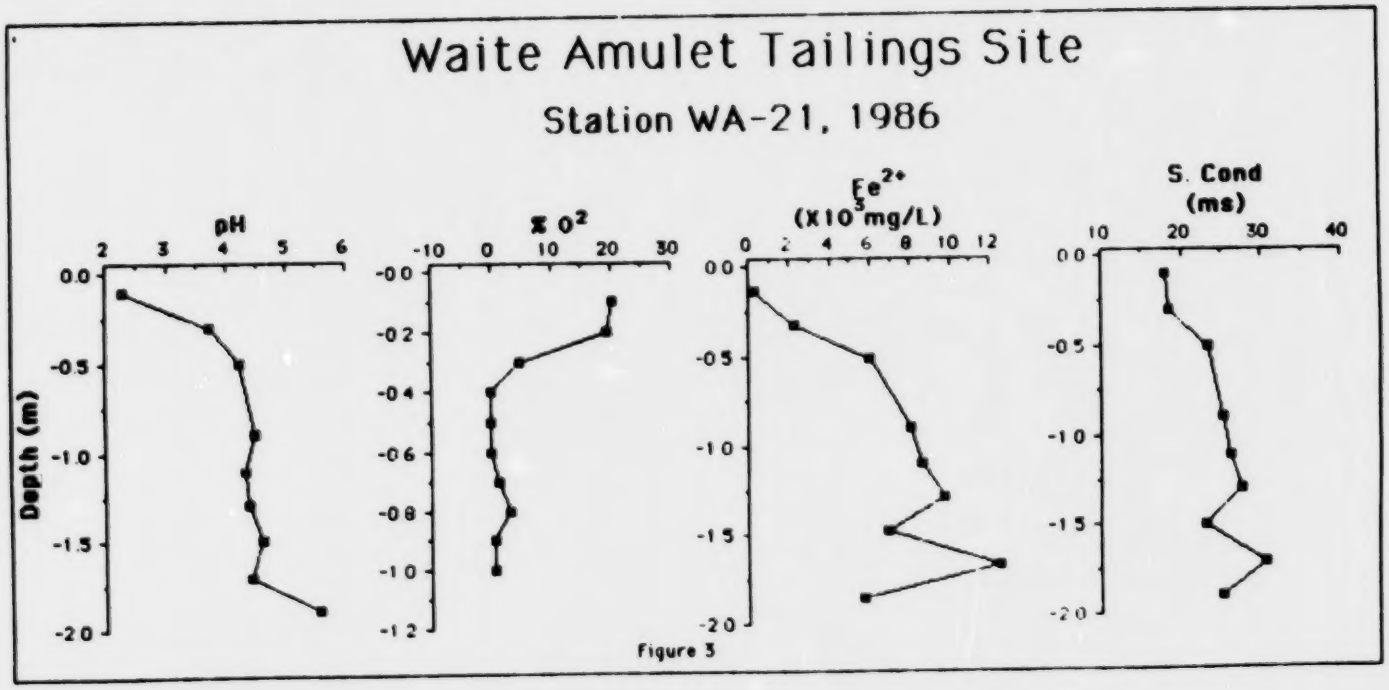
Figure 2

high, demonstrating an abundance of oxidized species in solution at shallow depths. Concentrations of Fe^{2+} increase in the vadose zone as illustrated in Figure 3 as O_2 is consumed in the pyrite oxidation reactions. The solution pH increases with depth as the O_2 concentration declines. Similar changes in tailings pore water geochemistry were observed at each sampling location. The depth of the low pH, high redox potential zone was observed to increase with O_2 penetration which in turn was a function of the distance to the water table. Pore waters with high Fe^{2+} concentrations and specific conductance have been displaced downwards past the water table by the gradual infiltration of rainwater and snowmelt.

5.3 A High Carbonate Tailings Site, Ontario

Tailings containing approximately 4% sulphide and 20% carbonate minerals were deposited from the early 1940's to the early 1960's. The mill at this site extracted gold from the sulphide-bearing, carbonate-rich ore. A successful vegetation program was initiated in 1971 on the 30 ha tailings surface.

Investigations included pore water sampling in the unsaturated and saturated zones and gas sampling in the vadose zone at several locations on and adjacent to the tailings pond.


Waite Amulet Tailings Site
Station WA-21, 1986
Depth (m)
pH
2 3 4 5 6
0.0 -0.5 -1.0 -1.5 -2.0
% O2
-10 0 10 20 30
-0.0 -0.2 -0.4 -0.6 -0.8 -1.0 -1.2
Fe2+
(X10-3mg/L)
0 2 4 6 8 10 12
0.0 -0.5 -1.0 -1.5 -2.0
S. Cond
(ms)
10 20 30 40
0.0 -0.5 -1.0 -1.5 -2.0
Figure 3

No acidic pore waters were detected. High concentrations of Fe^{2+} and specific conductance observed in the vadose zone indicate pyrite oxidation is occurring (Figure 4). The high pH levels suggest that the buffering capacity of the carbonate minerals and the rate of carbonate dissolution are sufficient to consume the H^+ generated by pyrite oxidation. Concentrations of other metals (Cu, Pb, Zn, Ni) exist at shallow depths in the unsaturated zone (Figure 5). It is likely that these elements were released to solution as a result of sulphide mineral oxidation.

5.4 Nordic Mine Tailings, Elliot Lake, Ontario

The Nordic Mine tailings, composed mainly of silicate minerals - approximately 5% pyrite and 0.06% calcite - were deposited from 1957 to 1968. A successful vegetation cover was established between 1973 and 1978. Blair et al., 1980, Dubrovsky et al., 1981, Smyth, 1982, Morin et al., 1982 have investigated the vadose and groundwater zones at several locations on and adjacent to these tailings.

The results of the investigations are summarized by Dubrovsky et al. (1985). These authors observed that low pH, high Fe^{2+} and SO_4^{2-} waters are present at shallow depths at each of the sampling locations. Dubrovsky (1986) suggests that the high Fe^{2+}, SO_4^{2-} pore waters are being

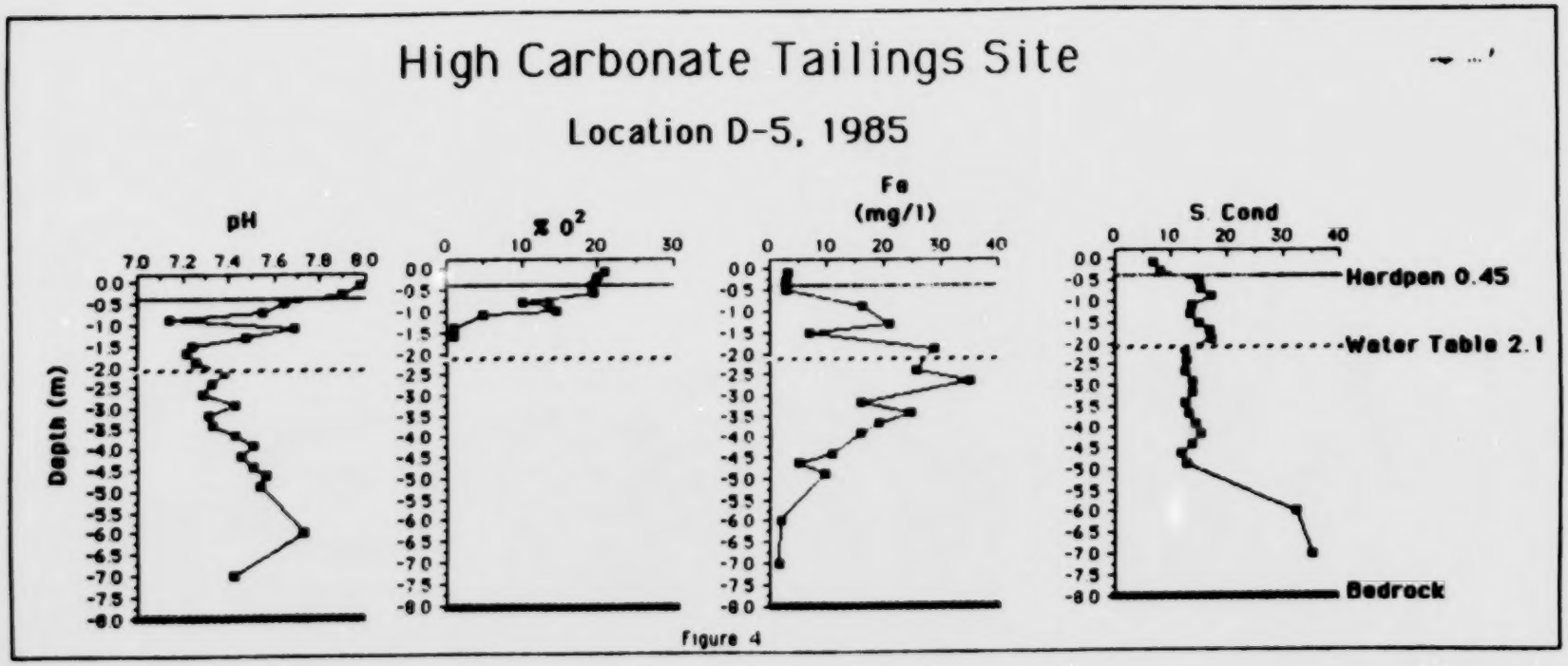

High Carbonate Tailings Site
Location D-5, 1985
pH
% O^2
Fe (mg/l)
S. Cond
Depth (m)
Hardpan 0.45
Water Table 2.1
Bedrock

Figure 4

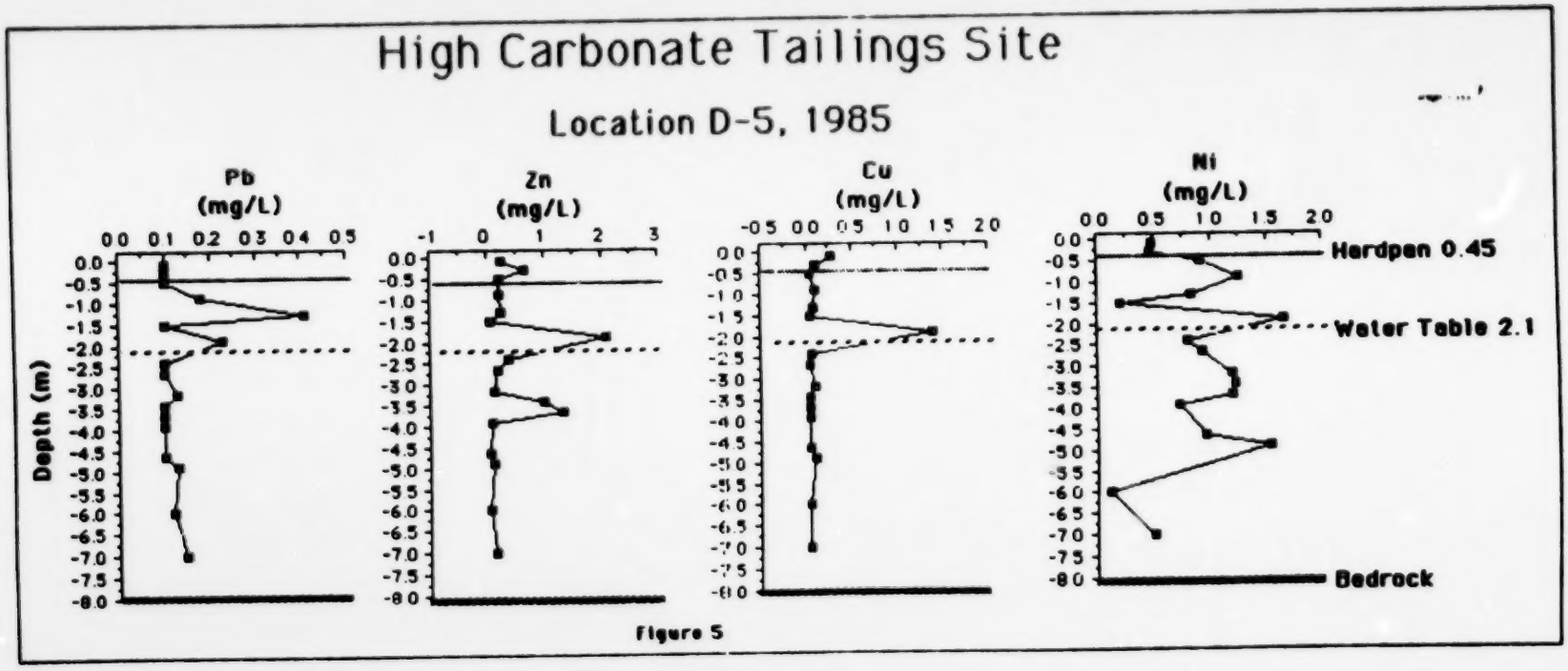

High Carbonate Tailings Site
Location D-5, 1985
Pb (mg/L)
Zn (mg/L)
Cu (mg/L)
Ni (mg/L)
Depth (m)
Herdpen 0.45
Water Table 2.1
Bedrock

Figure 5

displaced downwards through and out of these tailings by infiltrating rainfall and snowmelt at 0.24 to 2.0 m/a (average of 1.0 m/a), and that the low pH pore waters are being neutralized by carbonate consuming reactions.

Smyth (1982) concluded that the effects of pyrite oxidation were greatest at locations where the water table was deep and the tailings were coarse and, therefore, where O_2 diffusion would be greatest.

6.0 Discussion

Oxidation of sulphide minerals was evident in the upper 1 to 2 m of the vadose zone in the four tailings impoundments which were investigated. The extent of oxygen diffusion into the tailings is dependent on the depth of the water table and the sulphide content and particle sizing of the tailings. It appears to be independent of the presence of vegetation. Tailings with high pyrite content consume O_2 rapidly, and, therefore, the O_2 penetration depth is limited by this factor.

The oxidation of sulphide minerals generates low pH conditions and releases various constituents, principally Fe^{2+} and SO_4^{2-}, as well as concentrations of Cu, Pb, Zn, Ni and As. High concentrations of Fe^{2+} represent a large

potential source of acidity; each mole of Fe^{2+} will generate two moles of H^+ as a result of oxidation and precipitation of ferric hydroxides.

The H^+ generated by pyrite oxidation is neutralized by H^+ consuming reactions - the dominant process being the dissolution of carbonate minerals as described by the reaction

$$CaCO_3 + 2H^+ \rightleftharpoons H_2CO_3 + Ca^{2+}$$

under low pH conditions. This process can raise the pH to neutral or basic levels at which many metal concentrations will be controlled by hydroxide solubility constraints. Metal levels not influenced by precipitation-dissolution reactions may be controlled by adsorption-desorption processes on the surfaces of tailings solids and by co-precipitation. The mechanisms will depend on the bulk solution chemistry and on pH conditions. The overall effect of carbonate consuming reactions is to retard the movement of low pH fluid and, in many cases, high metal concentrations relative to the movement of infiltrating water through and out of the tailings impoundment.

At the high carbonate tailings location, the neutralization capacity was large enough to maintain neutral to alkaline pH conditions throughout the mass, including the vadose zone.

The elevated pH at this site limited metal concentrations to much lower levels than were observed at any of the other higher sulphide tailings ponds.

Pore water is being displaced downwards through the vadose and into the groundwater zone at each location due to infiltrating rainfall and snowmelt. Pore waters containing Fe^{2+} and SO_4^{2-} will eventually be displaced out of the tailings impoundment, either into the underlying groundwater flowsystem or into the surface seepage system. In the Nordic Mine tailings, the high Fe^{2+} and SO_4^{2-} pore waters have entered the underlying aquifer (Dubrovsky et al., 1985) while at Waite Amulet the discharge is via seepage along the flanks of the pond.

7.0 Conclusions

A self-sustaining vegetative cover can be established directly on reactive tailings. Rapid techniques for assessing the application rate of fertilizer, seed and alkali and for designing a vegetation program have been developed. Vegetation effectiveness in controlling acid generation, however, is limited, if not negligible. Based on preliminary information evolving from the RATS and the University of Waterloo research, the following conclusions have been formulated:

7.1 Pyrite oxidation is occurring within tailings containing 4-90% sulphide minerals independent of a vegetative cover. Metals such as Fe^{2+}, Zn, Pb, Cu, Ni, and As, and SO_4^{2-} are being released to the pore water in this oxidative zone.

7.2 Processes of neutralization, precipitation, co-precipitation and adsorption also occur within tailings below the reactive zone. The data from the four tailings sites illustrate a decrease in some metal concentrations and an increase in pH as the pore water is displaced downwards. With time, this flow will report either to groundwater or to surface seepage.

7.3 The zone of active sulphide oxidation is a direct function of the depth of oxygen penetration. This may be controlled by the depth of the water table and by the sulphide content and particle sizing of the tailings. Significant quantities of reactive tailings remain above the water table at each of the sites and as these sulphides are consumed, the downward flow of reaction products will continue.

7.4 Direct vegetation of reactive tailings does not restrict pyrite oxidation nor does it limit water infiltration sufficiently to significantly reduce water flow from the impoundment. Direct vegetation may cause the average water table to recede during the growing season and, therefore, the total mass of sulphides available for oxidation may increase.

7.5 The rate of acidity and heavy metal discharge from a reactive tailings mass cannot be predicted or modeled based upon the existing level of understanding of the geochemistry. Ongoing research efforts within RATS and the University of Waterloo program will address these unknowns.

Appendix A

Field Methods

Pore water from the tailings vadose zone was sampled using the modification of the Patterson et al. (1978) technique described by Smyth (1982). Samples were obtained at approximately 20 cm intervals throughout the unsaturated layer.

Vadose zone pore gas samples were collected using the method described by Reardon and Poescente (1984), and analyses were determined using a portable meter (Nova model 305LBD). Pore gas samples were also returned to the laboratory and analyzed by gas chromatography.

Water samples from the groundwater zone were collected using modified Cassagrande drive point piezometers of the type described by Dubrovsky et al. (1981). Samples were collected using the syringe sampling technique of Gillham (1982).

Pore water samples retained for analyses by atomic absorption were acidified immediately with concentrated HCl and refrigerated. Ferrous iron was determined in the field using the potassium dichromate method (Waser, 1966). The pH and redox potential of the pore waters were measured using a liquid filled combination pH electrode (Orion Ross) and a

combination platinum electrode (Orion 96-78). Electrodes were calibrated using pH 1.7, 4.0 and 7.0 buffers which were maintained at groundwater temperatures. Measurements of pH and redox potential in the saturated zone were made in closed flow-through cells also maintained at groundwater temperatures.

Appendix B

Geochemical Processes

Geochemical reactions which control pore water chemistry are oxidation-reduction, dissolution-precipitation, coprecipitation and adsorption. The dominant reaction in the geochemical evolution of tailings pore water is the oxidation of pyrite to produce low pH conditions and high concentrations of Fe^{2+} and SO_4^{2-}. The oxidation of pyrite may be described by the reaction

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

Nicholson (1984) suggested that in tailings environments the rate of pyrite oxidation is limited by the rate of oxygen diffusion into the tailings impoundment.

Ferrous iron in solution may be further oxidized to ferric iron through the reaction

$$Fe^{2+} + 1/2\ O_2 + H^+ \rightarrow Fe^{3+} + H_2O$$

Ferric iron can then precipitate as ferric hydroxide to release an additional three moles of hydrogen ion through the reaction

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$$

Ferric iron can also oxidize additional pyrite or other sulphide minerals through reactions of the form

$$2MeS + 7/2\ O_2 + H_2O \rightarrow 2Me^{+} + 2SO_4^{2-} + 2H^{+}$$

where Me represents a metallic ion. Oxidation of pyrite and other sulphide minerals releases additional metals, particularly Cu, Ni, Pb, Zn and As into solution. These oxidation products are transported by the physical processes of advection, dispersion and molecular diffusion. Concentration of reaction products is also controlled by the geochemical processes of precipitation and dissolution, adsorption and desorption, and co-precipitation.

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THE REACTIVE TAILINGS PROGRAM AND HYDROGEOCHEMICAL STUDY AT THE WAITE AMULET TAILINGS SITE, NORANDA, QUEBEC

by

R. Siwik[1] and R. Prairie[1]

ABSTRACT

This paper is an update of a presentation to the Mineral Processers Conference([1]).

The national reactive tailings (RATS) program is a co-operative industry-government effort to develop practical techniques for closure of reactive tailings areas. Implementation of this program is expected to cost in excess of $5 million over the next five years. This paper summarizes the RATS program objectives and areas of research, and details the Noranda/CANMET project on the Waite Amulet tailings.

Geophysical and biohydrogeochemical investigations were carried out at an inactive copper-zinc mine tailings site, Waite Amulet, in Noranda, Quebec. Geophysical investigations consisted of seismic, electromagnetic conductivity and electrical resistivity surveys to determine the thickness of the layers above bedrock and to map conductivity variations within the tailings and the immediate outlying area. Biohydrogeochemical investigations consisted of installing multilevel piezometer nests to determine groundwater flow patterns and porewater chemistry, obtaining solid core samples and characterizing for physical, chemical and mineralogical parameters, and iron oxidizing and sulphate reducing bacterial counts.

The geophysical survey indicated a bedrock ridge extending under the tailings from the northeastern outcrop which may act as a porewater boundary layer. The survey also indicated a 2 to 20 m

clay layer underlying the main tailings dam. The underlying clay layer is relatively impervious, and most of the seepage from the tailings is probably exiting from the sides of the impoundment dam. Preliminary results of the saturated zone porewater chemistry have indicated the pH is generally greater than 5 with low metal levels. A mineralogical examination in the saturated zone indicated minimal or no signs of alteration. In the unsaturated zone, the pH increased with depth from less than 3 to 6. Bacterial analysis showed a strong presence of Thiobacillus ferro-oxidans in the upper 2 m of tailings (8,000 to >100,000 MPN/g). Sulphate reducing bacteria were not detected in a majority of samples below the water table. The mineralogy indicated a strongly oxidized zone depleted of sulphides. Studies are currently underway dealing with monitoring oxygen diffusion, metal dissolution and transport, and oxidation control techniques.

The success of the RATS program requires commitment of funds and resources by both industry and government. Until cost-effective and environmentally-acceptable abandonment techniques have been demonstrated, it is recommended that governmental authorities be flexible in settling and enforcing reclamation guidelines.

1. Noranda Research Centre, Pointe Claire, Quebec

Presented at APCA/Québec, 15e Congrès Annuel, 27-29 mai 1987, Montréal, Québec.

1. INTRODUCTION

There are approximately 9000 hectares of acid-generating sulphide or reactive tailings in Canada. Effort in the past decade has focused on establishing a vegetative cover for reactive tailings as a method of final abandonment. This technique alone has not provided a walk-away situation due to the poor water quality associated with reactive tailings([2]).

The mining industry approached the federal government in late 1983 regarding the prospect of a co-operative program to solve problems associated with the closure of reactive tailings sites. Ths led to the development of the joint industry/government Reactive Tailings (RATS) program with the objective of([3]): "Producing an inventory of practical techniques which will enable the impact of acid-generating tailings and waste rock to be sufficiently reduced so as to allow for their ultimate abandonment without the need for on-going treatment or maintenance."

Federal and provincial governments as well as major mining companies are required to participate in this program to achieve this objective over the next five years at a cost in excess of $5 million.

The areas of research that are ongoing or are scheduled include:

- Establishing barriers to control the movement of water and oxygen. This would include engineered solid covers, underwater disposal, wet covers such as wetlands and high moisture-retaining material, and the development of hardpan.

- Investigation of the use of downstream passive control technology such as wetlands for polishing seepage discharge.

- Providing a state of the art review for disposal technology, long-term structural stability of tailings dams and the establishment of vegetation.

- Preparing field and analytical manuals to ensure quality control during sampling and analysis.

- Developing predictive techniques (modelling) for long-term predictions of various disposal options.

- Developing new tailings disposal technologies and mine close out techniques at mine opening.

- Incorporating National Uranium Tailings Program output into the Reactive Tailings Program.

Various mining companies including Inco, Falconbridge, Cominco and Noranda have been actively involved in projects which fall within the context of the RATS program.

Noranda has been extensively involved in setting up the RATS program, developing and monitoring the technical program and undertaking a major joint Noranda/CANMET field program at the abandoned Waite Amulet site.

2. WAITE AMULET STUDY OBJECTIVES

This five-year project jointly funded by Noranda Inc. and CANMET was initiated in June 1985. The project objectives are to:

. Develop improved long-term tailings management practices.

. Develop a better understanding of the hydrogeochemical processes and changes which occur in an acid-generating tailings area.

This study will establish the basic hydrogeology and geochemistry of the Waite Amulet tailings and indicate where the acid generation is occurring, what are the regulating factors and how can they be controlled. This study will also provide baseline data for a generic model development which will provide evaluation of long-term behaviour of reactive tailings under a wide range of disposal and reclamation scenarios.

3. HISTORY OF THE WAITE AMULET

The Waite Amulet tailings area, which is situated approximately 20 km north of Noranda (Figure 1) ceased operation in 1962 leaving 5.9 million tonnes of reactive sulphide tailings in an elevated 41 hectare dam and tailings spills in a lower area. Acid seepage and tailings surface runoff are collected in an acid water reservoir. A computer controlled high density sludge lime neutralization plant utilizes lime to neutralize, precipitate and remove metals to provide an acceptable effluent.

3.1 History of Mining Operations([4])

In August of 1928, mining of the Amulet ore began with ore averaging 8.1% Cu, 4.9% Zn and 2 oz/ton Ag being shipped to the Noranda Horne Smelter operations. In 1929, the 272 tonnes/day Amulet mill was constructed. In 1933, the Waite-Ackerman-Montgomery and Amulet shares were incorporated into Waite Amulet Mines Ltd. With the war demand for zinc, a new 1088 tonnes/day mill went into production to treat 816 tonnes/day of Cu-Zn ore from the Amulet Dufault and 272 tonnes/day from the Waite orebodies. A 300 tonnes/day mill extension went into operation in 1943. The mill then treated 907 tonnes/day of Lower "A" ore, 408 tonnes/day of Waite ore and 317 tonnes/day from the Amulet "C" orebody. The original Waite mine terminated in 1948. The Amulet "C" orebody was exhausted in 1951.

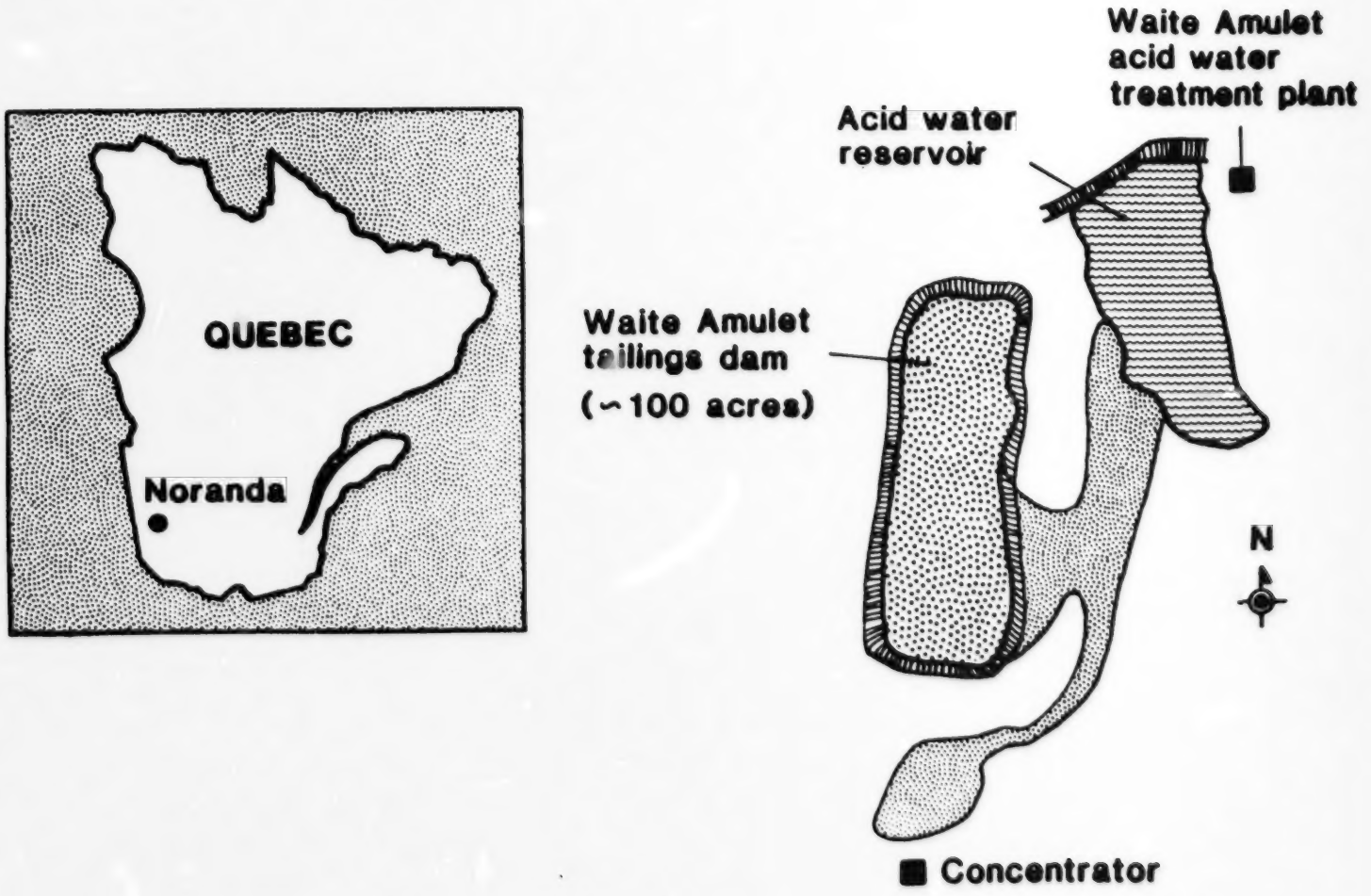


Figure 1 - Waite Amulet Tailings Area

The mill capacity was increased in 1955 to treat 907 tonnes/day of West MacDonald ore. Waite Amulet production was reduced to 907 tonnes/day. A pyrite flotation circuit was installed to produce a pyrite concentrate. An aerial tramway was used to transport the West Macdonald ore situated on the east side of Lake Dufault, to the Waite Amulet mill. The West Macdonald operation ceased in 1958. The only remaining orebody, the Amulet Dufault Lower "A", was exhausted in October 1962.

In total, ten orebodies were milled and the tailings disposed of in the Waite Amulet mill tailings area. Approximately 8.74 million tonnes were milled from the nine Waite Amulet and Amulet Dufault orebodies of which 2.65 million came from the Waite-Ackerman-Montgomery property, 1.17 million from the Amulet and 4.63 million from the Lower "A" Amulet orebodies. The West Macdonald orebody contributed approximately 0.81 million tonnes.

3.2 History of Milling Operations

The 1814 tonnes/day mill treated 907 tonnes/day of West Macdonald ore and 907 tonnes/day of Waite Amulet and Amulet Dufault ores. The Waite ores were approximately 60% sulphides (chalcopyrite, marmatite, pyrite and pyrrhotite) and the West Macdonald ore consisted of 95% sulphides, mainly pyrite and marmatite with minor amounts of chalcopyrite, pyrrhotite and galena.

The Waite gangue consisted of diabase and feldspar porphyry. Gangue from the West Macdonald ore consisted of lamprophyre and rhyolite.

The Waite Amulet mill flowsheet is illustrated in Figure 2. The Waite Amulet and West Macdonald grades and reagent consumption are detailed in Table I.

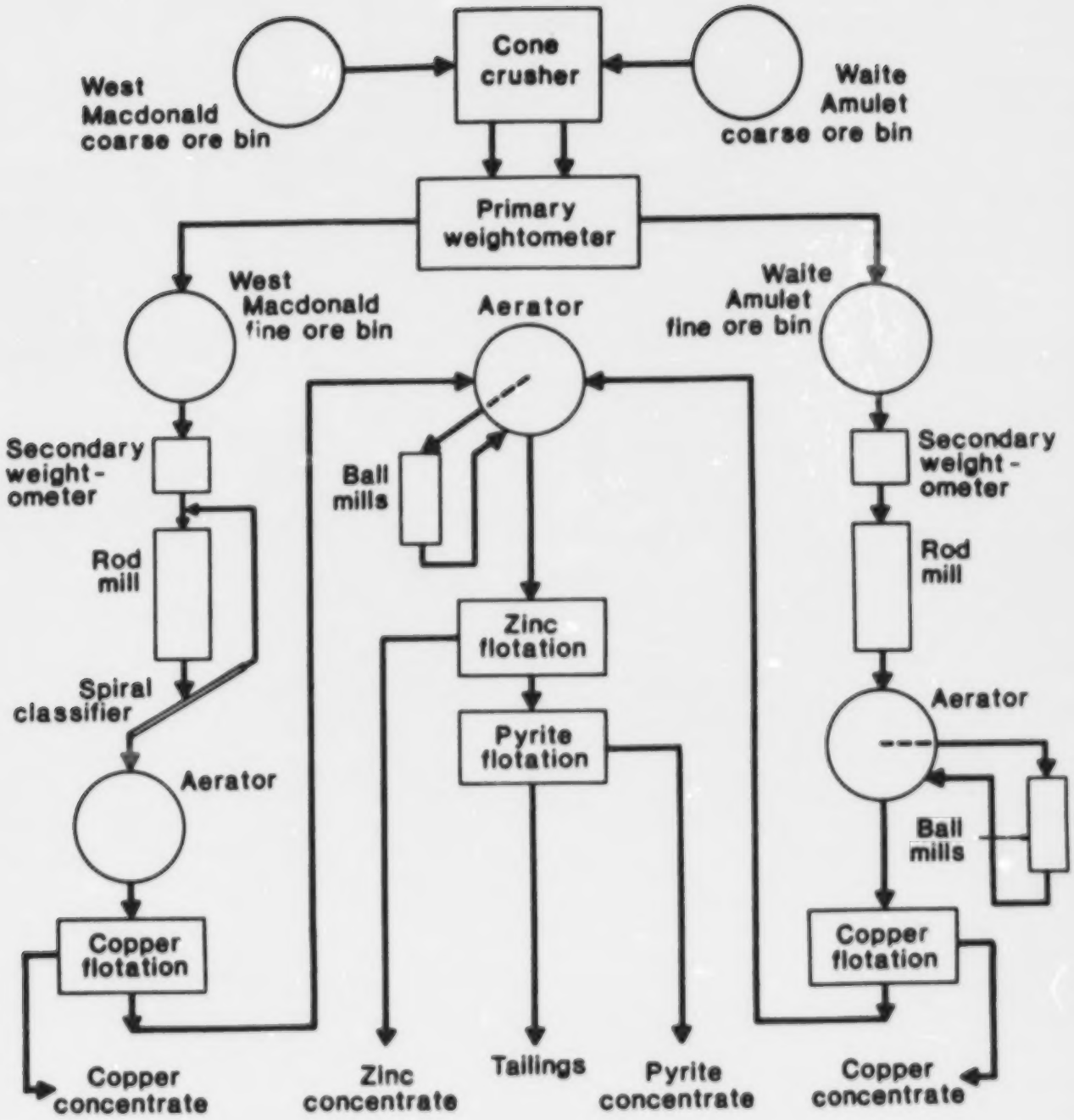


Figure 2 - Waite Amulet Mill Flowsheet (1956)

TABLE I

WAITE AMULET AND WEST MACDONALD METALLURGY (1956) AND REAGENTS

METALLURGY

	Cu %	Zn %	S %	Au oz/ton	Ag oz/ton
Waite Amulet ore	3.89	3.95	18.91	0.041	8.93
Recoveries (%)	94.49			65.41	65.33
West Macdonald ore	0.13	2.41	46.47	0.027	0.82
Recoveries (%)	7.62			7.53	6.47
Combined zinc recovery (%)		85.6			
Pyrite recovery (%)			83.2		
Pyrite tailings	0.16	0.26	12.82		

REAGENTS

	Waite Amulet Cu Flotation	West Macdonald Cu-Ag-Au Flotation	Zinc Flotation	Pyrite Flotation
Sodium sulphide (lb/ton)	1.086	0.302		
NaCN	0.028	0.007	1.870	
Soda Ash	2.336	1.650		
Aerofloat 242	0.066	0.013		
Z-5	0.074			
Frother 73	0.073	0.012	0.065	0.017
Aerofloat 208		0.005	0.093	
$Ca(OH)_2$			0.329	
$CuSO_4$			1.437	
$(NH_4)_2SO_4$			0.185	
Aerofloat 343				0.162

3.3 History of the Tailings Area

No available literature discusses the placement and operation of the 41 hectare main tailings dam. The tailings were gravity fed from the mill via a wood stave pipeline and trestle. The method of tailings dam construction may have been with original waste rock starter dams with subsequent lift construction using coarser spigotted tailings. The tailings were end spilled during winter operation in the central north and south sections.

The area between the concentrator and main tailings dam contains varying depths of tailings (1-2 m). Placement details are not known, but in the early 1920-1930's, tailings were probably disposed in this lower region and later, spills from the wood stave pipeline probably contributed.

3.4 Tailings Reclamation

The Horne Division's first full-scale revegetation attempts in the late 1960's were unsuccessful due to the high acidity of the tailings and the revegetation techniques utilized. These problems were eventually solved with the help of researchers from the University of Guelph([5]).

The majority of the main sulphide tailings dam was revegetated in 1978 and 1979. The pH of the tailings surface was neutralized with 44 tonnes/hectare of agricultural limestone. Up to 5.3 tonnes/hectare of fertilizer was used because these tailings are devoid of any nutrients. Birdsfoot trefoil and a companion crop of creeping red fescue were planted.

The acidic seepage from the Waite Amulet tailings site is presently being collected in an acid reservoir, illustrated in Figure 1, for treatment in an automated computer controlled high density water treatment plant.

4. METHODS OF INVESTIGATION

The following section reviews the methods of investigation for the geophysical survey, tailings hydrogeology, tailings porewater geochemistry, tailings mineralogy and bacterial presence. This material is taken mainly from a recent project reports([4,7]) and presentations([1,2,6]).

4.1 Geophysical Methods

As a part of the preliminary hydrologic survey of the Waite Amulet site, a geophysical survey was undertaken to determine the thickness of the tailings and the underlying clay, topographic variations in the underlying bedrock and electrical conductivity variations across the tailings. The geophysical investigations consisted of seismic refraction, electromagnetic and electrical resistivity surveys.

Seismic refraction data give detailed vertical information along traverses. Electromagnetic surveys give broad lateral information across the site. Resistivity soundings are used to give site-specific variations in vertical electrical conductivity. The penetration depth of these methods are variable and are used to examine variations in electrical conductivity across the site.

4.1.1 Seismic Refraction

The seismic refraction technique measures variations in the velocity that a shock wave or pulse propagates along boundaries of geologic units. It is assumed that seismic velocities of various units increase with depth as is generally the case.

A vibration is created by either a sledge hammer blow or a small explosion. To detect the vibration, a series of geophones is used. Typically, 12 geophones are placed at regular intervals from the source of vibrations. Close to the source, the first vibration reaching the geophone has travelled in a straight line along the surface. A plot of travel time versus distance from the source produces a straight line with a slope that is the inverse of the material velocity. As the distance between the source and geophone is increased, a critical distance is reached where the first vibration to arrive at the geophone is no longer the one travelling along the surface. This vibration has travelled down to a deeper, higher velocity layer, moved along it and has come back to surface. At distances greater than the critical distance, the difference in first arrival travel path for subsequent geophones is an increase in distance along the lower layer. The slope of the time-distance plot becomes the inverse of the higher velocity in this layer.

Using the source at either end of the geophone spacings, the interface of the high velocity layer, can be calculated using the delay time method presented by Redpath([8]).

4.1.2 Electromagnetic Terrain Conductivity Measurement

The Electromagnetic (EM) system used in this study was designed by Geonics. It is a two coil system. A current moving through the transmitting coil creates a primary electromagnetic field. This field penetrates the ground and induces a small current flow within the earth. The small current creates another (the secondary) EM field. The properties of the secondary field are a function of the electrical conductivity of the ground. Therefore, by detecting the combined primary/secondary field with another coil (the receiver) and removing the effects of the primary field, the ground electrical conductivity is determined. The instrument yields a bulk conductivity for the earth, down to

a penetration depth controlled by the inter coil spacing and orientation.

4.1.3 Electrical Resistivity Measurements

Direct current resistivity soundings measure the apparent resistivity of the ground through which an induced electrical current passes. The resistivity of the ground varies according to the grain size and water content of the material through which the electrical current passes. A current flow is induced through the ground between two electrodes. Two other electrodes are used to measure the potential voltage drop in the ground between the two electrodes. The depth of penetration of the electrical current is directly proportional to the distance between the current electrodes. By systematically increasing the distance between current electrodes, vertical variations in electrical conductivity, and hence variations in stratigraphy, can be measured.

4.2 Hydrogeological Investigations

The hydrogeological investigations consisted of installing piezometers at various locations, single or in multilevel piezometer nests throughout the site. By monitoring piezometric pressure heads, groundwater flow directions and hydraulic gradients were established.

Piezometers installed in the tailings were a modified Casagrande drive-point type, developed at the University of Waterloo([9]), constructed entirely of PVC material. A porous polyethylene cartridge with a 50 um pore size was used for the piezometer screen. The porous cartridge formed a sleeve over a 15 cm by 3 cm schedule 80 PVC perforated barrel. The porous cartridge was placed between the drive point tip and female coupling and sealed

with a silicone compound. Piezometers were installed by hand using a percussion drill in areas of fine grained material and shallow water table. In other places, the installation was done using a track mounted CME75 drill and hollow stem auger. Holes were augered to 1 m above the desired depth of the piezometer, and the latter then driven by hand 0.5 to 1.0 below the lead auger to allow the installation of the piezometer in relatively undisturbed tailings. At a given site, a series of piezometers was installed at different depths with vertical spacing of approximately 1.5 m between piezometers at each nest. Piezometers installed in clay underlying the tailings were slotted schedule 40 PVC pipe ranging in length from 0.6 m to 3 m. These piezometers were installed inside the hollow stem augers and were gravel packed with 0.6 cm washed pea gravel and a bentonite seal placed above the gravel pack. Figure 3 shows the piezometer locations. A total of 73 piezometers was installed at 27 nest locations.

After installation, the water level in the piezometers was measured routinely until steady-state was established. By monitoring the water levels, hydraulic gradients were established indicating groundwater flow directions. Hydraulic conductivities of the tailings material surrounding each piezometer were determined using the Hvorslev rising head test. The water column in a piezometer pipe is pumped out and the rate of inflow of water is measured during the recovery. With the measured recovery rate and the shape of the piezometer (i.e., length and diameter of the water intake zone), the hydraulic conductivity of the tailings in the immediate vicinity of the piezometer can be determined.

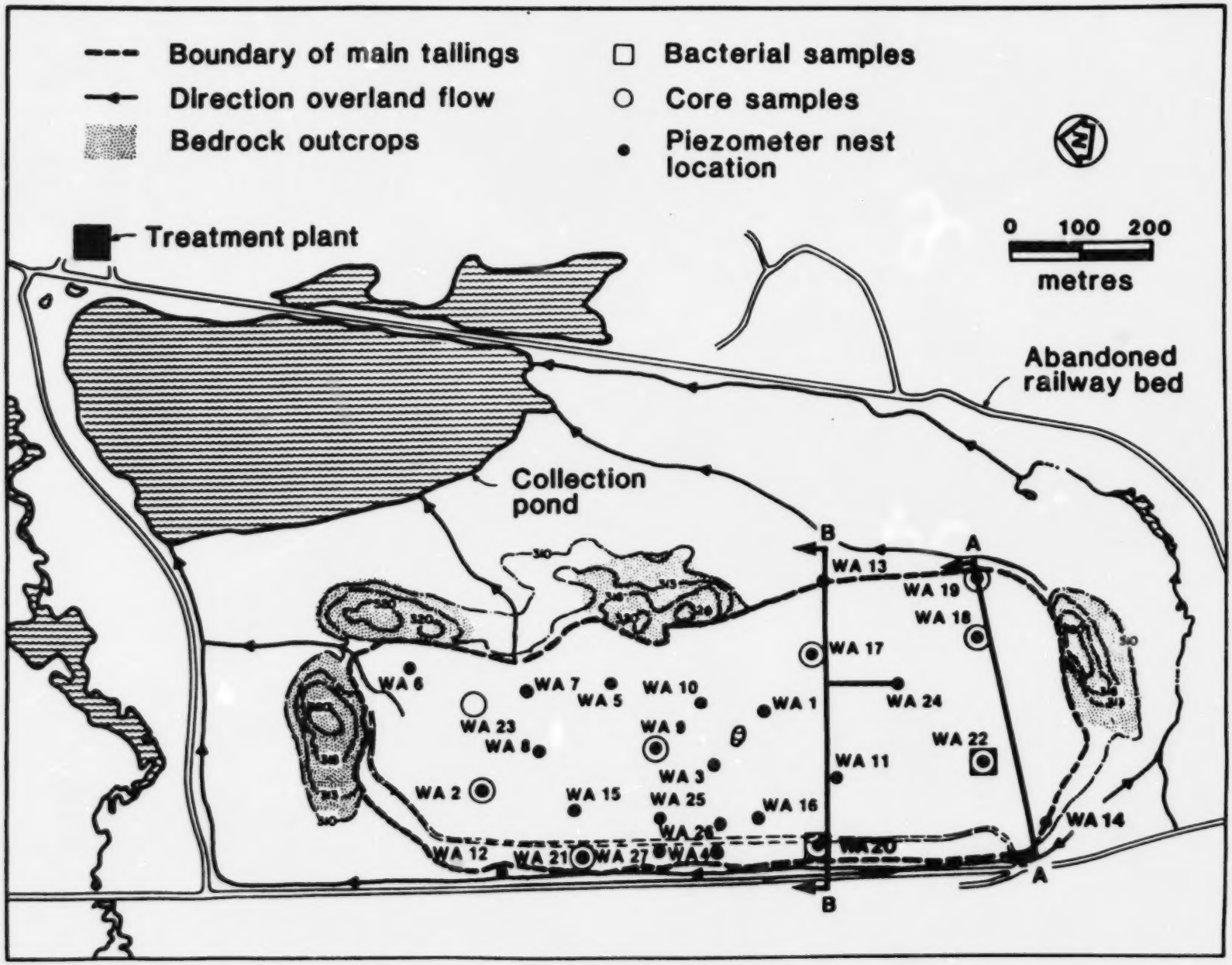


Figure 3 - Waite Amulet Tailings Site Sample Locations

4.3 Geochemical Investigations

For geochemical investigations, both tailings solid core and water samples were obtained. The solid samples were characterized for principal physical parameters, e.g. moisture content, grain size, porosity, etc., and mineralogy. Chemical profiles were measured for both solid and liquid samples.

4.3.1 Solid Sampling

Solid sampling was performed at nine locations illustrated in Figure 3 as WA2, WA9, WA17, WA18, WA19, WA20, WA21, WA22 and WA23. Six of the locations were on top of the main tailings area, while the other three locations were on the bench area of the tailings dam. The samples were obtained by a specially designed continuous soil sampler which fitted inside a hollow stem auger of I.D. 10.8 cm. The sample barrel was a split barrel which was advanced with auger advancement during drilling. The position of the sample barrel was adjusted to have a portion of it ahead of the augers, or just up inside the lead auger. The adjustment depended upon the hardness and cohesiveness of the material being sampled. The continuous samper system did not turn with the augers as it was advanced, and was in fact pushed ahead similar to obtaining a Shelby tube sample. The sampler was 1.5 m in length and 8.25 cm in diameter. Depending on the material being sampled, the length of the samples collected (i.e. lengths of auger advancement) varied from 0.75 m in regions of high water content and relatively incohesive material, to 1.5 m in the unsaturated and clay zones. The solid cores were sub-sampled for physical, chemical and biological characterizations.

4.3.2 Water Sampling - Saturated Zone

After installation, all the piezometers were cleaned, either by pumping out, or lifting the water with a gas lift pump using compressed nitrogen. Fresh water samples were obtained using a

peristaltic pump, filtered in the field with 0.45 um membrane filter and a glass fibre pre-filter. Temperature, pH, Eh, electrical conductance, acidity, alkalinity and Fe^{+2} for water samples were measured in the field. The samples were then acidified with HCl (final concentration 2% acid) and preserved for laboratory analyses for major cations and anions.

4.3.3 Water Sampling - Unsaturated Zone

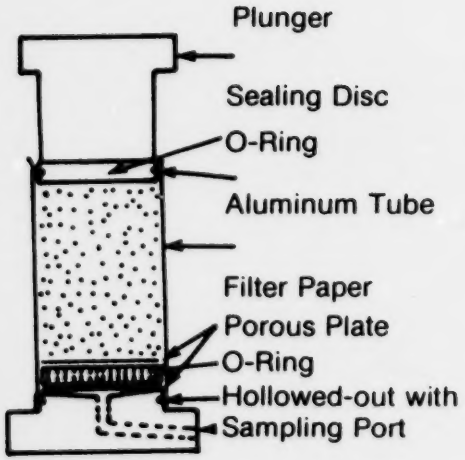
This work was undertaken by D. Blowes, University of Waterloo. Core samples were collected from the unsaturated zone using aluminum tubing. A squeezing apparatus illustrated in Figure 4 was used to displace the pore water in the unsaturated zone. Approximately 40 mL of sample was collected.

4.4 Biological Investigations

The biological investigations consisted of analyzing the solid core samples for iron-oxidizing Thiobacillus ferro-oxidans and sulphate reducing organisms. Two of the nine core samples, one from the main tailings, and the other from the perimeter dam were analyzed. For bacterial counts, the core sample were sub-sampled. These sub-samples were then placed in sterilized sample containers and refrigerated prior to analysis. Care was taken not to expose samples to the outside environment which would be detrimental to the bacterial populations, especially to the oxygen-sensitive sulphate reducers.

The method of enumeration for Thiobacillus ferro-oxidans and sulphate reducers was a 5 x 5 most probable number (MPN) where 5 replicates of 5 dilutions of each sample were employed. the MPN method, in each case, provided an estimate of the number of bacteria per gram dry weight of tailings sample.

Squeezing Apparatus



Squeezing Apparatus and Stand

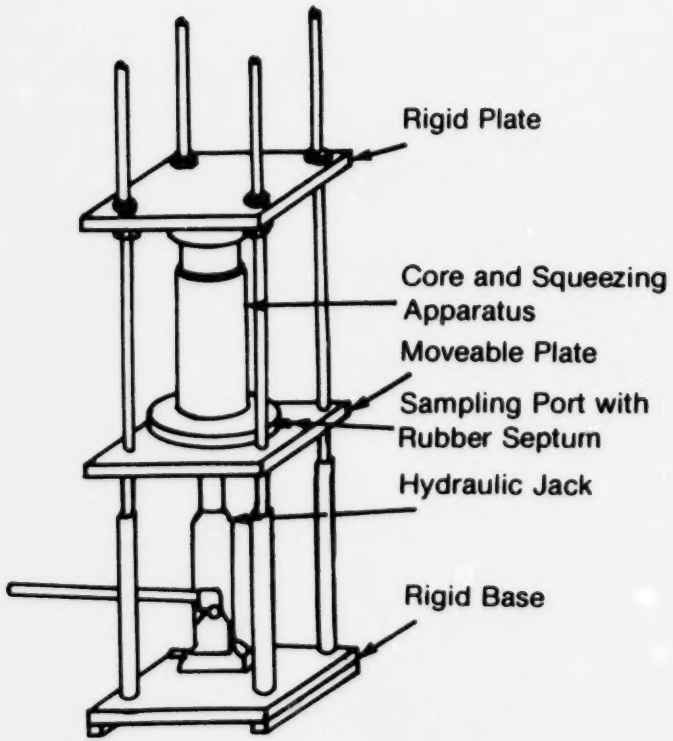


Figure 4 - Core Squeezing Apparatus and Stand

4.5 Pore Gas Sampling

Pore gas was sampled using 0.64 cm O.D. stainless steel tubes driven into the tailings area. This work was undertaken by D. Blowes, University of Waterloo.

5. RESULTS AND DISCUSSION

5.1 Geophysical Results

5.1.1 Seismic Survey

The seismic survey provided representative cross-sections of the site along the three survey lines. Over most of the tailings, four layers were identified as:

Layer 1 was a continuous surface unit with a seismic velocity of 300 m/s. This layer represented unsaturated and very poorly consolidated tailings or fill.

Layer 2 with a velocity of the order of 600 m/s represented saturated tailings. The unit was continuous and varied in thickness from 2 to 10 m over the site.

Layer 3 was identified as a clay layer based on the drilling results. The seismic velocity is 1100 m/s, and the thickness varied from less than 2 m to 21 m. The elevation of the top of layer 3 varied by 5 m over the site.

Layer 4 was identified as bedrock with a velocity of 5,980 m/s. The bedrock surface was irregular with over 15 m of relief across the site.

Core logs from holes WA9 and WA22 (Figure 3) provided the control

for the seismic results as these holes were near the seismic lines.

5.1.2 Electromagnetic and Electrical Resistivity Surveys

These provided the apparent thickness of tailings and depth to the bedrock, but only very approximately as the data could only be interpreted for a two-layer system.

Based on these results and drilling logs, the site can be described as:

Tailings: The thickness varied from 2 m to about 15 m. The thickness increased to the south-west, filling any depressions in the surface of the clay. The seismic velocity of the tailings was uniform and more typical of unsaturated materials. The electrical conductance was variable but always high, about 100 to 400 mS.

Clay: The surface of the clay was moderately irregular as it sloped to the south and west across the site. Its thickness varied from 2 to 20 m, thinning on bedrock highs. It has a fairly uniform seismic velocity.

Bedrock: The topography of exposed bedrock around the site and underneath was extremely variable. Bedrock elevations decreased to the south-southeast across the site. At least two, and possible three, ridges trending northeast-southwest appeared to extend from bedrock outcrops to the tailings.

Further analysis of geophysical techniques is awaiting the mineralogical assessment and a complete water chemistry survey of the saturated and unsaturated zone.

5.2 Groundwater Flow System

Figure 5 shows the general water table configuration across the tailings area obtained in October 1985. The water table varied from just below the ground surface in the north and central portions of the site to 5.5 m below ground surface in the southern part. The piezometer data showed wide variation in hydraulic gradients across the site. The horizontal gradients varied from 0.007 in the south west (i.e., WA14) to 0.04 in the north west (i.e., WA12, WA21). The vertical gradients ranged from almost non-existent at WA22 to greater than 0.5 at WA2.

Based on the water table configurations and vertical water level profiles, it appears that porewater within the tailings is generally moving outwards from the centre of the tailings through the coarse grained tailings dam and discharging into the surrounding drainage ditch, either directly, or as a seepage across the tailings dam. The elevation of water level and flow along these seepage lines increased very quickly after rainfall events.

Because of its low permeability, the underlying clay would act as a barrier to the downward movement of porewater from the tailings in the south portion of the site. In the north portion, it appeared that there was little hydraulic connection with the shallow bedrock in the northeast, but there may be good hydraulic connection in the northwest direction where a high hydraulic conductivity zone below the tailings was observed.

Hydraulic conductivities ranged from 9×10^{-7} cm/sec to 1.4×10^{-3} cm/sec. Low hydraulic conductivities, $\sim 10^{-6}$ cm/sec, were generally found in the north end of the tailings where fine grained tailings were deposited. The highest hydraulic conductivities ($\sim 1.2 \times 10^{-4}$ - 1.4×10^{-3} cm/sec) were generally found in the south end of the tailings and along the perimeter of the dam. The porewater horizontal velocities within the tailings ranged

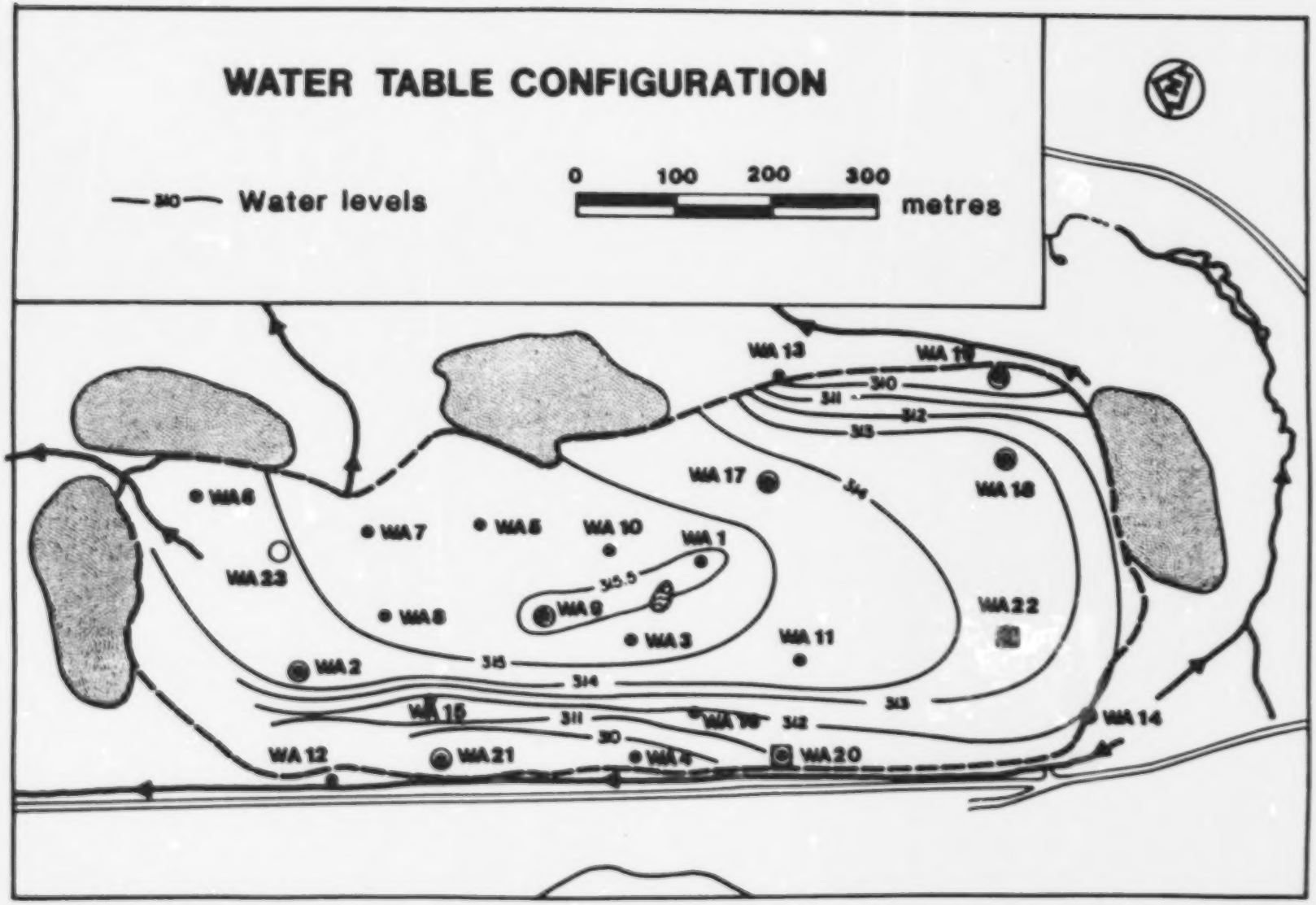


Figure 5 - Waite Amulet Tailings Water Table and Piezometer Location, October 1985

from 0.4 cm/y to 5 m/y. Tailings porewater velocities across the tailings dam were calculated up to 35 m/y indicating the majority of the tailings porewater exits from the dam sides.

5.3 Porewater Chemistry and Pore Gas([7])

The results of the piezometer sampling conducted in 1986 showed that the pH below the water table across the site was generally greater than 5. There is little evidence of vertical profile trends in pH below the water table other than the slightly lower pH in the porewater zone just below the water table. The pH in the unsaturated zone was generally less than 3 near surface and increased with depth([1,2,4,6,7]).

Figures 6 and 7 show the chemical profiles of tailings porewater as a function of depth for the Sections A-A and B-B (See Figure 3). Concentrations of SO_4^{-2} and Fe_T decreased with depth below the water table as the neutral pH zone was approached. This is caused by the neutralization of the acidic porewater, and hence precipitation of metal hydroxides as it migrates downward. The degree of neutralization depended upon the presence of resident alkaline buffers in the tailings.

Monitoring the pore gas for O_2 in the unsaturated zone indicated O_2 penetration was generally less than 1 m. This is consistent with the oxidation profile and gaseous O_2 entry may control oxidation.

5.4 Solid Phase and Bacterial Analysis

Figure 8 shows the solid phase pH and bacterial counts for Thiobacillus ferro-oxidans reported as most probable numbers (MPN/g) as a function of depth for two bore holes WA20 and WA22. For WA20, mineral compositions for pyrite, pyrrhotite, and

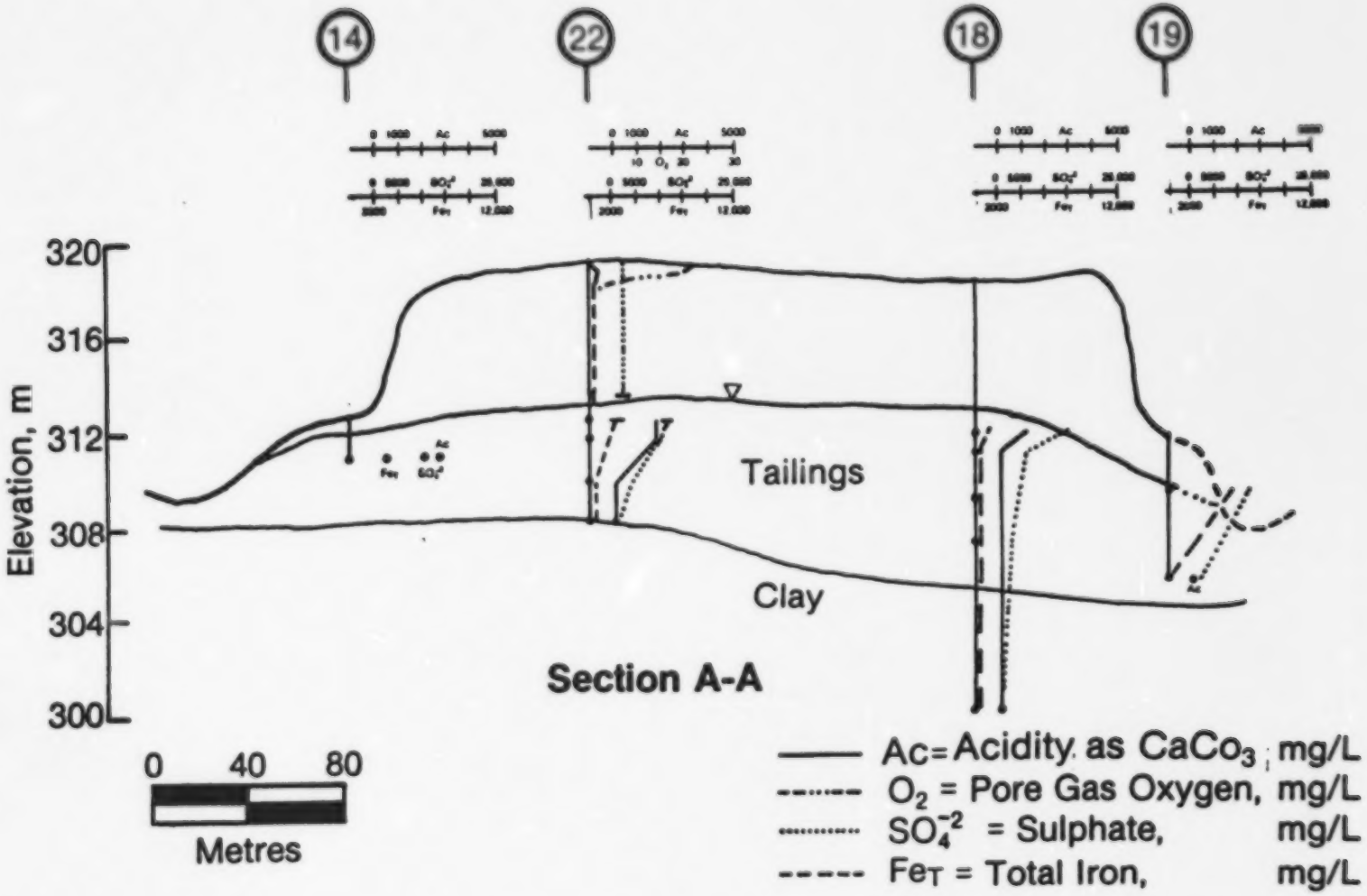


Figure 6 - Section A-A, Waite Amulet Tailings

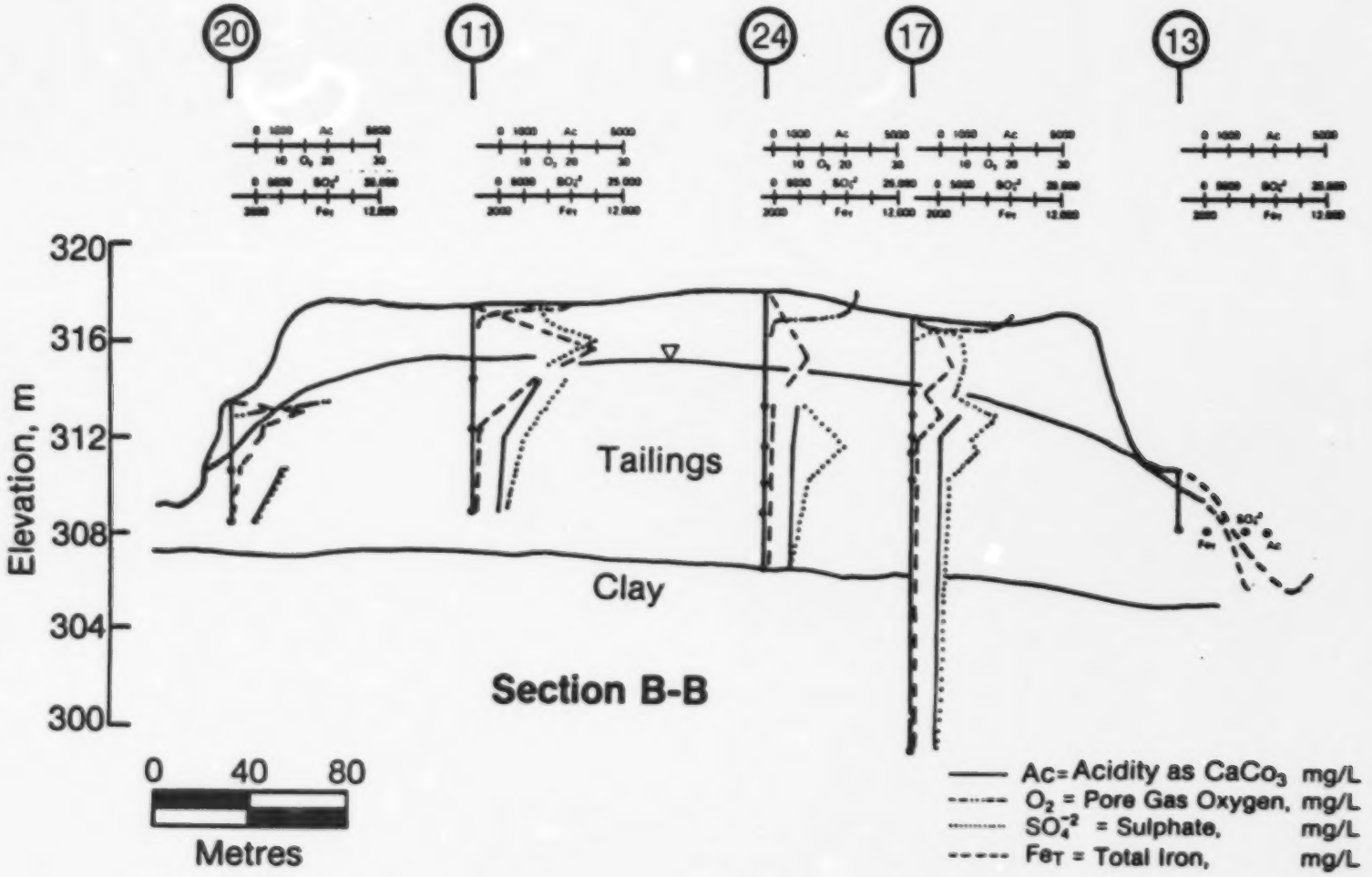


Figure 7 - Section B-B, Waite Amulet Tailings

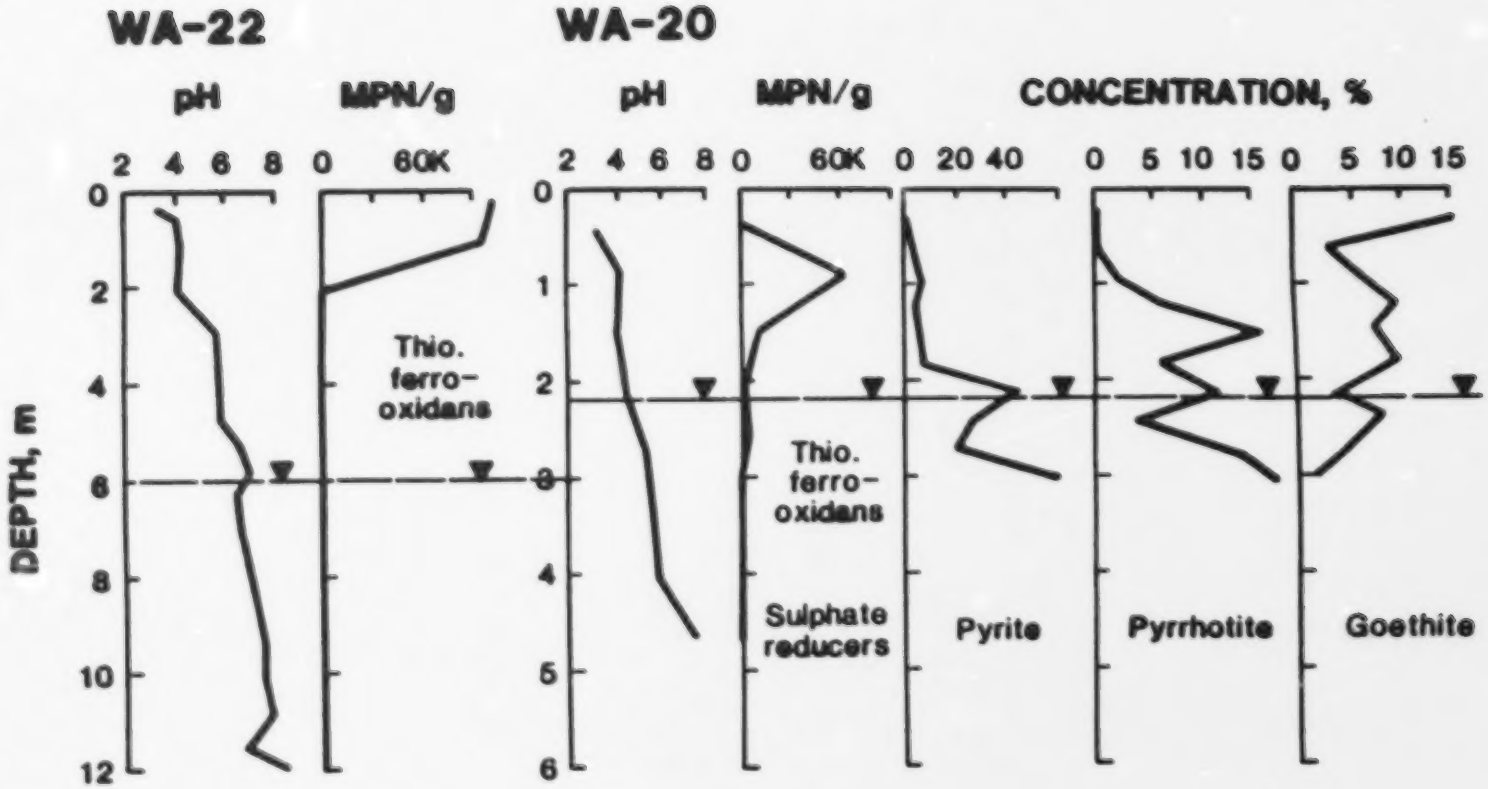


Figure 8 - Solid Phase Tailings Profiles for pH, Thiobacillus ferro-oxidans for WA22 and WA20 and Pyrite, Pyrrhotite and Goethite for WA20

altered oxidation product goethite are also shown([6]).

The bacterial results showed a strong presence of iron oxidizing Thiobacillus ferro-oxidans above the water table at both locations. Their activity profile indicated the most active oxidation strata in the vadose zone. Petruk([10]) obtained similar results for oxidation profiles from mineral compositions for WA20 where oxidation has been completed in the uppermost layer, progressing faster in the unsaturated zone above the water table and progressing slowly near the water table in the saturated zone. For most of the solid samples analyzed, sulphate reducers were not present. Mineralogical analysis of the saturated zone by J. Jambor, MSL, CANMET([11]) indicated only local alteration of pyrrhotite. Therefore, oxidation below the water table is negligible.

6. ON-GOING AND 1987 STUDY PROGRAM FOR WAITE AMULET

The third year of a proposed five-year $550,000 field program will:

- initiate the collection of data for evaluation of metal loadings and hydraulic regime using equipment installed in 1986;
- continue the evaluation of the geochemistry of the clay-covered, directly-vegetated and untreated sites, and along the sloped dam face;
- relate the mineralogy and geochemistry in the unsaturated zone;
- continue evaluation of gaseous O_2 profiles;
- define oxidation control options for the 1988 field season.

An understanding of the hydrochemical processes and controlling mechanisms in the unsaturated zone will provide information on the effectiveness of various existing and new tailings disposal practices. This project and other projects currently underway in the RATS program should provide the mining industry with techniques to decommission sites in a more cost-effective and certain manner. The success of the RATS program requires committment of funds and resources by both industry and government to demonstrate effective and environmentally-acceptable abandonment techniques.

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